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The Effect of Variation in Early Summer Rainfall Patterns on Blacklegged Tick (Ixodes scapularia) Nymph Survival, and the Implications for the Transmission of Lyme Disease in Connecticut

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Abstract

Lyme disease is a vector-borne disease, transmitted to humans by the bite of the black-legged tick (*Ixodes scapularis*) infected with the spirochete *Borrelia burgdorferi.* This disease is endemic in Connecticut, and has been increasing in prevalence over the last 30 years. However, the incidence of Lyme disease fluctuates from year to year. Previous studies have demonstrated a possible link between Lyme disease incidence and moisture/drought conditions in late spring and early summer months in the northeast United States. Humans are usually infected by ticks in the nymphal stage of their life-cycle. In the current study, it is hypothesized that the apparent link between Lyme disease and moisture conditions results from the impact of moisture conditions on nymph survival. Thus, a two-year time lag in Lyme disease incidence and June moisture levels arises because nymphs that have started to feed over the course of the summer will be less likely to survive if conditions are drier than normal, leading to fewer larvae the following year, and fewer nymphs two years later. The reverse would be true for summers that are wetter than normal. *I. scapularis* nymphs were collected twice a month from 10 properties in Lyme, Old Lyme, Chester, and East Haddam, from May through August over a period of 19 years – 1989 through 2007. Ticks were tested for the presence of *B. burgdorferi*, and an Entomological Risk Index (ERI) (pop. Infected ticks) was determined. Summer moisture conditions – using both NOAA reported Palmer Hydrological Drought Indices and Palmer Z Indices – were predicted to correlate positively with summer nymph densities and ERI. Late spring/early summer moisture conditions were predicted to correlate positively with summer nymph densities and ERI

in the same year, and two years later. As predicted, nymph density and ERI did correlate positively with moisture conditions in the same year and two years previously ($p < 0.05$). These findings provide an explanation for the observation that June moisture conditions are linked to Lyme disease incidence in the same year, as well as two years later. The data further suggest that people who engage in activities in woodland habitats and woodland-field edges, particularly in early summer, are probably at greater risk in picking up *B. burgdorferi* infected ticks if the summer is wetter than usual, as well as when the summer two years previously was wetter than usual.

Introduction

Lyme Disease

Lyme disease is one of the most common vector-borne diseases in the United States. It is caused by infection with the spirochete *Borrelia burgdorferi* and transmitted to humans when bitten by infected *Ixodes* ticks.[1] Early symptoms include fever, headache, and fatigue, and 70-80% of infected people develop *erythema migrans* (EM), a characteristic dark red "bulls-eye" skin rash at the site of the bite. If left untreated, the disease can spread to other parts of the body resulting in a number of symptoms, including meningitis, pain in the joints, and later, arthritis, and chronic neurological complaints.[2] Cases of Lyme disease are most common in people aged 5-14 and 45-54 years of age.[3]

Lyme disease was long endemic in parts of Europe, but was recognized and described in the United States more recently. Although the first cases of EM were reported in Wisconsin and in southeastern Connecticut,[4] Lyme disease was first identified as a distinct clinical entity from a cluster of cases in Lyme, Connecticut, in 1975. Originally identified in Lyme as a new form of inflammatory arthritis[5], epidemiological evidence suggested that it was a vector-borne disease carried by ticks of the genus *Ixodes*. The causative agent, a spirochete (*Borrelia burgdorferi*), was isolated a few years later.[1]

Lyme disease has increased substantially in the northeastern United States over the last thirty years, due in part to changes in land-use practices and tick host densities.[6] Prior to the nineteenth century, ticks were abundant in the northeast. Then, as land was cleared for agriculture, populations of white-tailed deer were drastically reduced due to

loss of habitat and over-hunting. As white-tailed deer are an important host for ticks, tick numbers plummet when deer populations drop and remain low for a considerable period[7] But in the twentieth century, forest habitats replaced agriculture once more, deer populations flourished, and tick numbers increased yet again and spread. [6] With this spread came a greater human risk of infection with Lyme disease, as people have increased their odds of coming into contact with infected ticks by encroaching into wooded habitats where ticks are found.[8] In the northeast, most cases of Lyme disease appear to be acquired from ticks picked up close around the home, as people build more homes in wooded areas.[8]

By 2005, the disease was endemic in the northeastern, mid-Atlantic, and two north-central states, including, Connecticut, Delaware, Maryland, Massachusetts, Minnesota, New Jersey, New York, Pennsylvania, Rhode Island, and Wisconsin. These 10 states accounted for 93% of the 64,382 Lyme disease cases reported to the Centers for Disease Control and Prevention (CDC) during 2003-2005.[3] In Connecticut, Lyme disease is a reportable disease, consisting of passive surveillance reporting by physicians statewide, and active reporting by participating physicians in 71 towns.[9] In 2005, 1,810 new cases of Lyme disease were reported in Connecticut with a rate of 51.56 per 100,000. In contrast, 23,305 total new cases and 7.85 per 100,000 were reported in 2005 for the United States as whole.[3] In 2007, 3058 cases were reported (90 per 100,000 pop.). The highest rates (per 100,000 pop.) in Connecticut were reported from Litchfield (206), Windham (180), New London (157), and Tolland counties (205).[10]

The Tick Life Cycle

In Connecticut, the vector for the spirochete *Borrelia burgdorferi* is the blacklegged tick, *Ixodes scapularis* (the deer tick). The life-cycle of the blacklegged tick takes two years in northern states with cold winters, such as Connecticut. It has four stages in the life-cycle, including the egg, larva, nymph, and adult (Figure 1). It also has a 3-host life-cycle from larva to adult. Eggs are laid in the spring, and larvae feed on small-sized hosts, such as mice, during the later summer months and over winter as nymphs in a dormant state. Larvae that survive the winter molt into nymphs the following spring. Nymphs usually feed primarily on small to medium-sized hosts during the summer months, including a large variety of birds and mammals. Only if they find such a host can they then molt and transition to the adult stage in the autumn. The adults then feed on a wide variety of medium to large-sized mammalian hosts, such as deer, through the fall and the following winter and spring. After they find a host, engorged females drop off and can lay over 2000 eggs.[8, 11]

Hosts and reservoirs for Borrelia burgdorferi

The principal reservoirs for *Borrelia burgdorferi* – the spirochete that causes Lyme disease – is the white-footed mouse (*Peromyscus leucopus*), the Eastern chipmunk (*Tamias striatus*), and possibly shrews.[8] The white-tailed deer (*Odocoileus virginianus*) is not a reservoir host for the spirochete, but as it is the primary host for adult ticks, it is key to their reproductive success. The larvae and nymphs of the blacklegged tick become infected when they feed on rodents.[8] Adults that have had more frequent exposures to infected hosts as larvae and nymphs, are more likely to be infected than nymphs.[8]

Factors that may increase risk of human exposure to infected ticks

Lyme disease risk clearly depends on exposure to infected ticks. The incidence of Lyme disease has been found to correlate with annual fluctuations in population densities of *I. scapularis*, specifically, with those infected with *B. burgdorferi*.[12] The Entomological Risk Index[13] (ERI) is a measure of the abundance of infected ticks calculated as nymphal density multiplied by the rate of infection with *B. burgdorferi*. Densities of ixodid ticks are higher in forested areas, preferably deciduous forest[14] followed by forest-field edges, and lowest in fields[15]. Thus, humans are at risk of exposure to infected ticks when they enter such habitats.[15] Most human Lyme disease infections are associated with nymphal ticks during June and July, rather than by adult ticks.[11] Larvae are rarely infected. Nymph densities peak in June[8], followed a month later by a peak in Lyme disease incidence[16]. Therefore, though humans are at risk of infection in tick habitats at all months of the year, they are more at risk from late May to August, and particularly in June[16], during peak outdoor tick and human activity.[17]

Nymph densities are influenced by host animal populations as well as environmental factors. In fact, climate factors may play a more important role, because of their direct effect on tick survival[18, 19], on host population survival[20], and on vegetation and tick habitat[21]. A couple of studies suggest indirectly that variations in precipitation patterns do impact nymph densities. For example, McCabe and Bunnell[22] found that, in the northeast United States, cases of Lyme disease were significantly and positively correlated with May and June precipitation of the same year. Thus, more cases of Lyme disease occur if late spring and early summer are wetter than average. However, Subak[11]

did not find such a strong correlation for same-year moisture index and Lyme disease cases in seven northeastern states (including Connecticut). Instead, she found that fluctuations in reported cases of Lyme disease positively correlated with rainfall patterns two years previously. Thus, according to Subak, higher rates of Lyme disease occur if the summer two years previously was wetter than average.[11] This suggests that variations in moisture levels at "Year 0" (Figure 2) can impact nymph densities in the early summer months two years later ("Two Years On", Figure 2), when the next generation of ticks are in their nymph stage of development.

Study Predictions

The fact that Lyme disease appears to correlate with spring/summer precipitation[11, 22] strongly suggests that May-June precipitation patterns impact tick activity or later tick survival, specifically nymphs. The goal of this thesis is to determine whether there is in fact a link between May-June precipitation patterns and nymph densities for *I. scapularis* nymphs collected in residential properties in southern Connecticut. These findings will help to clarify how climate variability in moisture conditions may impact tick activity and consequently the incidence of Lyme Disease in Connecticut. The following predictions were made. (To follow predictions, refer to Figure 2).

<u>Same-Year Predictions</u>:

McCabe and Bunnell[22] concluded that the increase in Lyme disease cases during wet summers is due to an increase in nymph survival rate and increased nymph activity

during wetter conditions in early spring and late summer of that year. If correct, it is predicted that,

1) there would be a positive correlation between moisture conditions and nymph activity in May and June of the same year; and
2) given the observation that Lyme disease incidence correlates with annual fluctuations in population densities of *I. scapularis* infected with *B. burgdorferi* [12], there would also be a positive correlation between May-June moisture levels and the ERI in the same year.

Predictions for Two Years On:

Subak[11] concluded that the increase in Lyme disease cases two years after wet summers is due to enhanced nymph survival rate during wet conditions, and that drought conditions primarily affect nymph survival. Note that the two-year time lag would mean the infected ticks in question would be the offspring of the nymphs affected by the May-June moisture levels two years previously (Figure 2). If Subak's conclusions are correct, it is predicted that,

3) there would be a positive correlation between May-June moisture conditions, and June nymph activity two years later (refer to Figure 2); and if so,
4) there would also be a positive correlation between May-June moisture levels, and the ERI two years later, given the observation that Lyme disease incidence correlates with annual fluctuations in population densities of *I. scapularis* infected with *B. burgdorferi* [12].

Predictions for One Year On

Subak's[11] findings would be explained if nymph activity two years on is partly linked to the survival of the eggs and larvae that produced those nymphs. She did not find a correlation between moisture conditions (when the cohort in question would be in its egg to larval stages, refer to Figure 2), and Lyme disease incidence one year on. She speculated that moist weather is unlikely to be a factor affecting larval survival. Therefore, it is further predicted that,

5) there would be little or no correlation between May-June moisture or drought conditions, and June nymph activity one year later,
6) there would little or no correlation between May-June moisture or drought conditions, and the ERI one year later

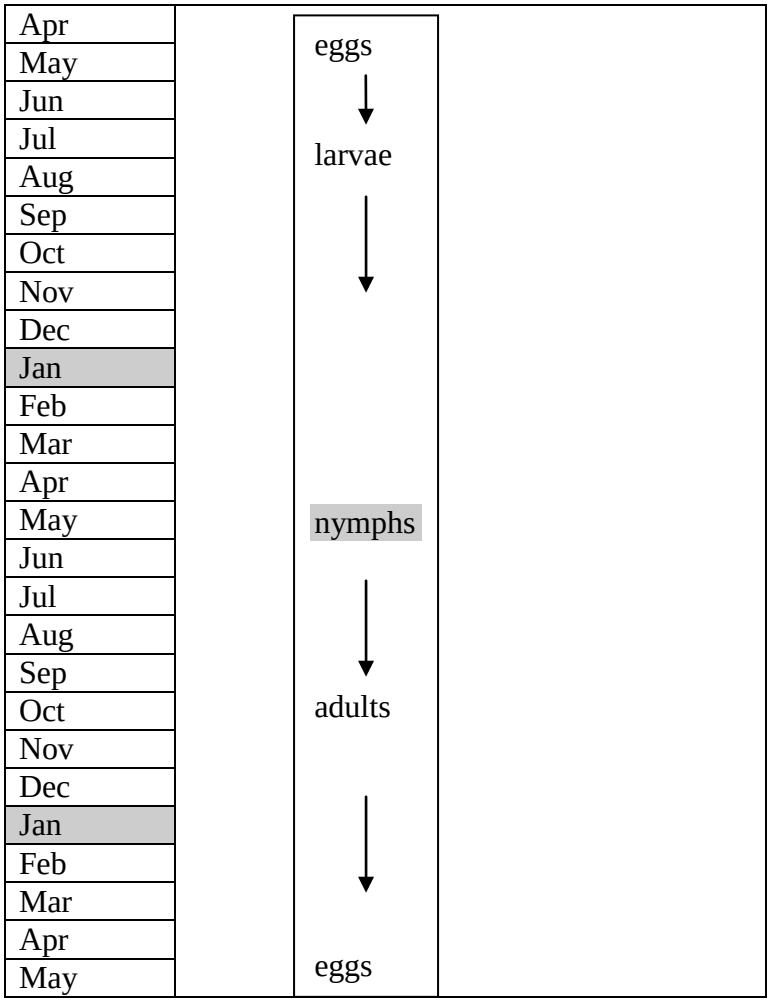


Figure 1. Two-year life-cycle for *Ixodes scapularis* in northern United States

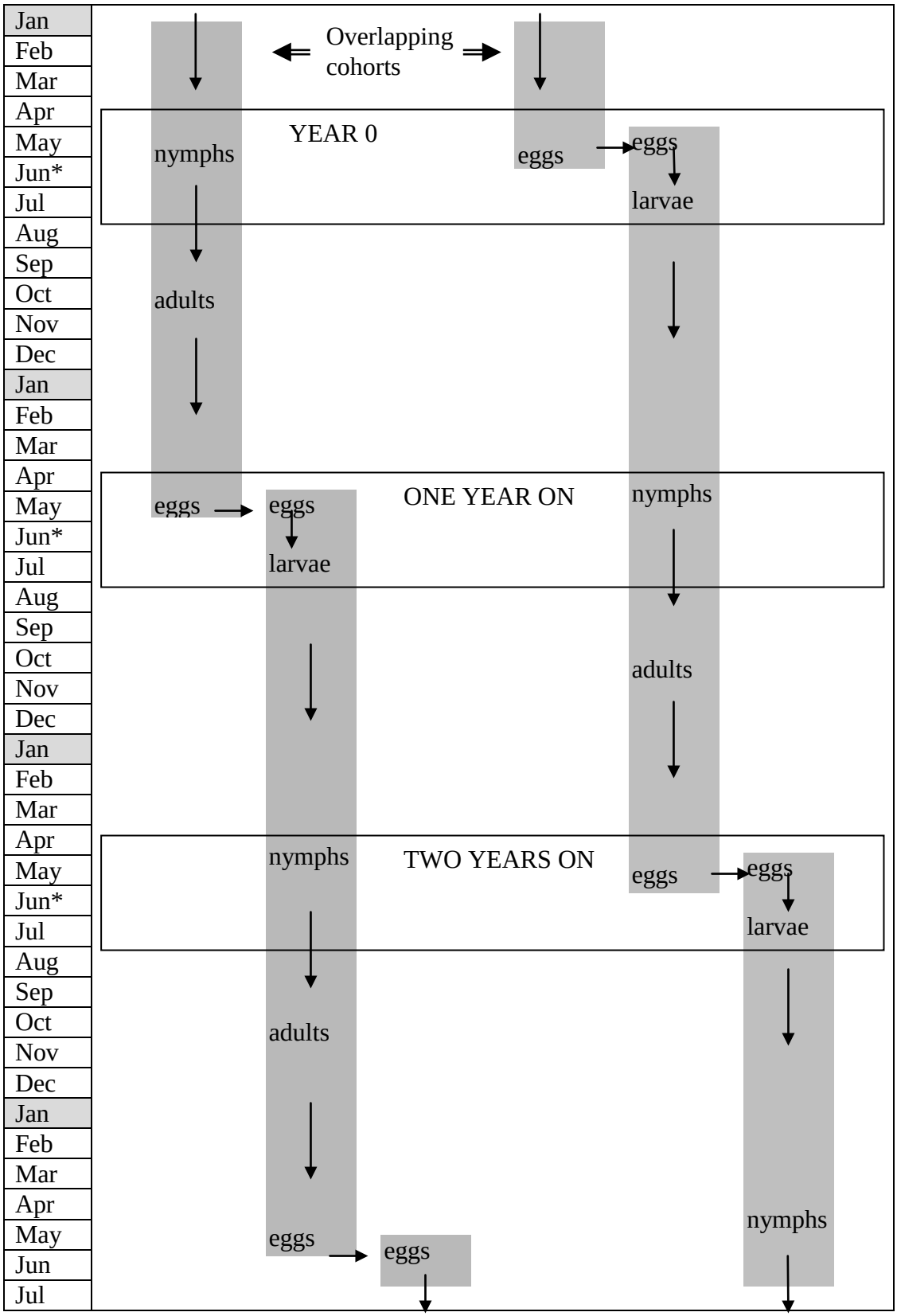


Figure 2. Nymphs at “Two years on” are from eggs laid by nymphs at “Year 0”.

Methods

Study design

Every year since 1989, Dr. Kirby Stafford III, Chief Scientist and State Entomologist at the Connecticut Agricultural Experiment Station in New Haven, hires research assistants to participate in the arthropod control programs through integrated pest management practices, including the control of ticks and Lyme Disease in Connecticut. Over the course of the summer, research assistants are sent to prime tick habitat to sample the abundance of ticks in those areas. Dr. Stafford kindly gave me permission to use the data he gathered with his research assistants on *Ixodes scapularis* nymphs towards testing the predictions of this thesis.

Tick sampling

Ixodes scapularis nymphs were collected from ten residential properties over the course of 19 years, from 1989 to 2007, in Lyme (four sites), Old Lyme (two sites), East Haddam (three sites), and Chester (one site). On each property, ticks were sampled from two different habitat types where *I. scapularis* predominates: woodland and woodland edge, designated as Woods and Lawn respectively. The total area sampled ranged from 0.32 to 0.91 hectares for Woods (mean 0.45 ha), and 0.88 to 1.89 ha for Lawn sites (mean 1.05 ha). The area measured was determined by rolling a metric measuring wheel along the perimeter of the site.

Nymphs were sampled by dragging a 1.2m^2 (95 cm x 130 cm) piece of white flannel cloth over the vegetation. The cloth was stapled along a 105 cm wooden dowel.

For Lawn sites, the cloth was dragged across the grass along the periphery of the woodland habitat. For Wood sites, the cloth was dragged back and forth in rows within the designated area in the woodland habitat. At the end of each drag row, ticks found attached to the cloth were removed. The removed ticks were placed in vials with a blade of grass for moisture, and returned to the Connecticut Agricultural Experiment Station for identification and for testing for *B. burgdorferi*. Each site was sampled every two weeks, from May to August. The presence of *B. burgdorferi* was determined by indirect fluorescent antibody staining of tick mid-gut tissues with a murine monoclonal antibody.[23] The ERI was determined by multiplying the mean number of ticks per hectare with the infection rate (% nymphs infected with *B. burgdorferi* out of total # nymphs tested).

Nymph activity is a relative estimate of nymph density, as one can only count those nymphs that are actively questing for a host and crawl onto the white flannel. Mean nymph densities for Lawn sites were determined for each month by adding the total number of nymphs collected for that month and dividing the sum by the sum of all Lawn areas sampled on each visit. Woods mean nymph densities were calculated in the same way, using Woods areas sampled. For both Lawn and Woods sites, mean densities were calculated for each month from May through August.

Climate data

Data on moisture conditions in the sampled regions was obtained from the NOAA Satellite and Information Service, National Climatic Monitoring Data Center website.[24] Two different moisture indices were used: the Palmer Z Index (PZI) and the Palmer

Hydrological Drought Index (PHDI), the latter used by Subak[11], which she termed the "moisture index". The PZI was used to see if short-term anomalies in moisture conditions impact nymph densities (i.e., nymph activity). The index indicates how monthly moisture conditions of short-term drought and wetness, depart from normal.[25] The index generally ranges from -2.75 to +3.5, with negative values indicating moisture anomalies in the dry direction, while positive values indicate anomalies in the wet direction (Table 1).[26] The PHDI was also used because it indicates the severity of a wet or dry spell in terms of monthly hydrological (long-term cumulative) drought and wet conditions, and more accurately reflects groundwater conditions and reservoir levels, which may reflect ground level moisture availability on nymph survival.[25] The index generally ranges from -6 to +6, with negative values indicating dry spells, and positive values indicating wet spells (Table 1).[26] Monthly PZI and PHDI scores were downloaded from the NOAA NCDC Climate Monitoring Data Center[24] for climatic division 3 (southern CT) (Appendix Figure A1), for the years spanning 1987 to 2007 (Appendix Table A1 & A2).

Statistical Analyses

Nymph densities vs. moisture conditions

Monthly PZI and PHDI scores for May through August, from 1987 through 2007 were correlated with nymph density means. To test predictions 1, 3 and 5, linear regression analyses were performed on May to August PZI and PHDI scores and 1) nymph densities for the same months of the same year, 2) nymph densities for June of the following year, and 3) nymph densities for June two years on. (For statistical correlations involving nymph densities one and two years on, June nymph densities were used as

nymph densities generally peak in this month.) Prediction 1 would be supported if June moisture indices were found to have a statistically significant positive correlation with June nymph densities of the same year (Figure 2). Prediction 3 would be supported if May-June moisture indices were found to have a statistically significant positive correlation with June nymph densities two years on (Figure 2). Prediction 5 would be supported if May-June moisture indices were found to lack a statistically significant correlation with June nymph densities one year on (Figure 2).

Nymphs infected with B. burgdorferi vs. moisture conditions

Monthly PZI and PHDI scores for May through August, from 1987 through 2007 were correlated with ERI to test predictions 2, 4 and 6. Linear regression analyses were performed on May to August PZI and PHDI scores and 1) ERIs for the summer of the same year, 2) in the summer of the following year, and 3) in the summer two years on. Prediction 2 would be supported if June moisture indices were found to have a statistically significant positive correlation with the ERI for the same year (Figure 2). Prediction 4 would be supported if June moisture indices were found to have a statistically significant correlation with the ERI two years on (Figure 2). Prediction 6 would be supported if June moisture indices were found to lack a statistically significant correlation with the ERI one year on (Figure 2).

Linear regressions

For Predictions 1 to 4, the predictions were met if they were both positive and statistically significant at $p \leq 0.05$. A 1-tailed Pearson's analysis was used since an

association was predicted in the positive direction only. For Predictions 5 and 6, the predictions were met if they were not statistically significant at $p \leq 0.05$. A 2-tailed Pearson's analysis was used since an association in either a positive or negative direction would mean the findings do not support the predictions. Correlations with $p \leq 0.10$ were also considered. Given the variability of field data, any real relationship may be missed if only correlations for $p \leq 0.05$ were considered. Field studies do not have the high degree of precision or control as laboratory studies.

The dependent (mean nymph densities and ERI) and independent variables (PZI and PHDI) were interval data, but may not meet the assumptions for parametric tests (i.e., equal variances and be normally distributed). Thus, 2-tailed Spearman's non-parametric linear regression analyses were also performed. Pearson's is a more powerful statistic, but if all the Spearman's analyses gave results that differed markedly from the Pearson's results, the findings using Spearman's would be considered only.

SPSS statistical software[27] was used for all correlations of variables in Tables A3, A4, A5 and A6 (Appendix) for all rows with no missing values. For correlations with PZI or PHDI with mean June nymph densities in the following years, the latter values were shifted up, so that, for example, SPSS would correlate 1989 June PZI with 1990 June mean nymph densities, and so on. Note that this all comes to 56 correlations, which in theory means that 56 x 0.05 = 2.8 statistically significant correlations could be found by chance alone. However, there is a biological mechanism to support the findings should they support the predictions, which reduces this concern.

Table 1. Classes for Wet and Dry Periods

Range PHDI	Category	Range PZI
> 4.00	Extreme wetness	> 3.50
3.00, 3.99	Severe wetness	2.50, 3.49
1.5, 2.99	Mild to moderate wetness	1.00, 2.49
-1.49, 1.49	Near normal	-1.24, 0.99
-1.50, -2.99	Mild to moderate drought	-1.25, -1.99
-3.00, -3.99	Severe drought	-2.00, -2.74
< -4.00	Extreme drought	< -2.75

PHDI = Palmer Hydrological Drought Index
PZI = Palmer Z Index
[From NOAA National Climatic Data Center[26]]

Results

Prediction 1: there would be a positive correlation between moisture conditions and nymph activity in May and June of the same year

Prediction 1 was supported for Lawn densities, but a negative correlation was found for Woods densities. There was a positive correlation ($r = 0.331$, $p = 0.083$, 1-tailed) between June moisture anomalies (PZI) and June Lawn nymph activity of the same year, although this was only statistically significant at $p < 0.10$ (Table 2, Figure 3). June PZI therefore only accounted for 11% of the variation in June Lawn nymph densities in the same year ($r^2 = 0.11$). In contrast, for Woods, June moisture conditions appeared instead to correlate inversely (PZI: $r = -0.371$, $p = 0.059$, 1-tailed; PHDI: $r = -0.471$, $p = 0.021$, 1-tailed) with June nymph densities, which was the opposite of that predicted (Table 3, Figure 3). In other words, when June was wetter than normal, nymph densities in the grass areas bordering woodlands (Lawn) were somewhat higher, while nymph densities in woodland habitats (Woods) dropped. The reverse occurred when June was drier than normal. The Spearman's analyses supported the findings for the Woods data, but not for the Lawn data (Table 3).

Prediction 2: there would be a positive correlation between May-June moisture levels and the ERI in the same year

Prediction 2 was supported for Lawn, but not for Woods. There was a positive correlation ($r = 0.387$, $p = 0.056$, 1-tailed) between June moisture anomalies (PZI) and ERI in the same year, although this was only statistically significant at $p < 0.10$ (Table 4). Fro Lawns, June PZI therefore only accounted for 15% of the variation in ERIs in the

same year ($r^2 = 0.15$). In other words, the ERI in the grass areas bordering woodlands (Lawn) were somewhat higher when June was wetter than normal, and lower when June was drier than normal. However, the Spearman's analyses found no statistically significant correlations for either Lawn or Wood of the same year (Table 4).

Prediction 3: there would be a positive correlation between May-June moisture conditions, and June nymph activity two years later

Prediction 3 was supported for both Lawn and Woods. There was a positive correlation between May, June and July moisture conditions (PHDI) and June Lawn nymph activity two years later (May PHDI: $r = 0.406$, $p = 0.042$, 1-tailed; June PHDI: $r = 0.345$, $p = 0.074$, 1-tailed; July PHDI: $r = 0.356$, $p = 0.067$, 1-tailed) (Table 2, Figure 4), as well as for May and June moisture conditions (PHDI) and June Woods nymph activity two years later (May PHDI: $r = 0.381$, $p = 0.054$, 1-tailed; June PHDI: $r = 0.309$, $p = 0.099$, 1-tailed) (Table 3). Note, however, only the May PHDI correlation with Lawn nymph densities was statistically significant at $p < 0.05$. The other four correlations were only statistically significant at $p < 0.10$. Late spring/ early summer PHDI therefore only accounted for up to 16% of the variation in June nymph densities two years later ($r^2 = 0.16$). In other words, when May and June were wetter than normal, nymph densities in both the grass areas bordering woodlands (Lawn) as well as in the woodland habitats (Woods) were somewhat higher two years later. The reverse occurred when May and June were drier than normal. The Spearman's analyses supported these findings (Table 3).

Prediction 4: there would be a positive correlation between May-June moisture levels, and the ERI two years later

Prediction 4 was supported for both Lawn and for Woods, but for May moisture conditions only. There was a positive correlation ($r = 0.455$, $p = 0.029$, 1-tailed) between May moisture conditions (PDHI) and Lawn ERI two years later, and a positive correlation ($r = 0.441$, $p = 0.034$, 1-tailed) between May moisture conditions (PDHI) and Woods ERI two years later. Both correlations were statistically significant at $p < 0.05$ (Tables 4 & 5, Figure 5). However, May PHDI only accounted for up to 21% of the variation in ERIs two years later ($r^2 = 0.21$). In other words, when May was wetter than normal, the ERI for the woodland habitats (Woods) as well as for the grass habitats bordering the woodlands (Lawn) were somewhat higher two years later, and somewhat lower when May was drier than normal. The Spearman's analyses supported these findings (Tables 4 & 5).

Prediction 5: there would be little or no correlation between May-June moisture conditions, and June nymph activity one year later

Prediction 5 was supported for Lawn, but not for Woods. Instead of the predicted lack of correlation, there was a negative correlation between May and June moisture anomalies (PZI) and June Woods nymph activity one year later, although this was only statistically significant at $p < 0.10$ (May PZI: $r = -0.416$, $p = 0.077$, 2-tailed; June PZI: $r = -0.395$, $p = 0.094$, 2-tailed) (Table 3). However, late spring/early summer PZI only accounted for up to 17% of the variation in May and June Woods nymph densities in the following year ($r^2 = 0.173$). In other words, when May and June were wetter than normal,

nymph densities in woodland habitats (Woods) were lower in June of the following year. The reverse occurred when May and June were drier than normal. The Spearman's analyses only supported the findings for Woods (Table 3).

Prediction 6: there would little or no correlation between May-June moisture conditions, and the ERI one year later

Prediction 6 was supported for both Lawn and for Woods. There was no statistically significant positive or negative correlation between May or June moisture conditions (PZI or PDHI) and Lawn or Woods ERI one year on (Tables 4 & 5). In other words, a wetter or drier May or June did not have an appreciable impact on the ERI the following summer, for either the woodland habitats (Woods), nor the grass habitats bordering the woodlands (Lawn). The Spearman's analyses supported the findings for Woods, but not for Lawn (Tables 4 & 5).

[See Appendix for tables of PZI, PHDI, mean nymph densities, ERI, and associated graphs.]

Table 2. Moisture conditions (PZI and PHDI) vs. mean Lawn nymph densities.

LAWN	Tick Densities (mean # nymphs per hectare)		
Moisture conditions	June Same Year	June Next Year	June Two Years On
May	--	--	**0.406**^{**H} (r_s = **0.486****)
June	0.331^{*Z} (r_s = 0.089^{Z} NS)	--	0.345^{*H} (r_s = 0.376 NS)
July	--	--	0.356^{*H} (r_s = 0.282 ^{H} NS)
August	--	--	--

-- results were not statistically significant ($p > 0.1$)
* r values are statistically significant at $p \leq 0.10$
** r values (in bold) are statistically significant at $p \leq 0.05$
Correlations are Pearson's correlation coefficients, unless otherwise indicated
r_s = Spearman's correlation coefficients; NS = not statistically significant at $p > 0.10$
Z = PZI, or Palmer Z Index; H = PHDI, or Palmer Hydrological Drought Index
Note: May, July and August nymph density correlations were not statistically significant at $p \leq 0.1$

Table 3. Moisture conditions (PZI and PHDI) vs. mean Woods nymph densities

WOODS	Tick Densities (mean # nymphs per hectare)		
Moisture conditions	June Same Year	June Next Year	June Two Years On
May	--	-0.416^{*Z} (r_s = **-0.463**^{**Z})	0.381^{*H} (r_s = **0.412** ** ^{H})
June	-0.371^{*Z} **-0.471**^{*H} (r_s = **-0.511**^{**H})	-0.395^{*Z} (r_s = -0.328 ^{Z} NS)	0.309^{*H} (r_s = 0.333^{H} NS)
July	--	--	--
August	--	--	--

-- results were not statistically significant ($p > 0.1$)
* r values are statistically significant at $p \leq 0.10$
** r values (in bold) are statistically significant at $p \leq 0.05$
Correlations are Pearson's correlation coefficients, unless otherwise indicated
r_s = Spearman's correlation coefficients; NS = not statistically significant at $p > 0.10$
Z = PZI, or Palmer Z Index; H = PHDI, or Palmer Hydrological Drought Index
Note: May and July nymph density correlations were not statistically significant at $p \leq 0.1$. August nymph densities had a r_s = -0.464 for PHDI, $p = 0.095$.

Table 4. Mean Lawn moisture conditions (PZI and PHDI) vs. ERI.

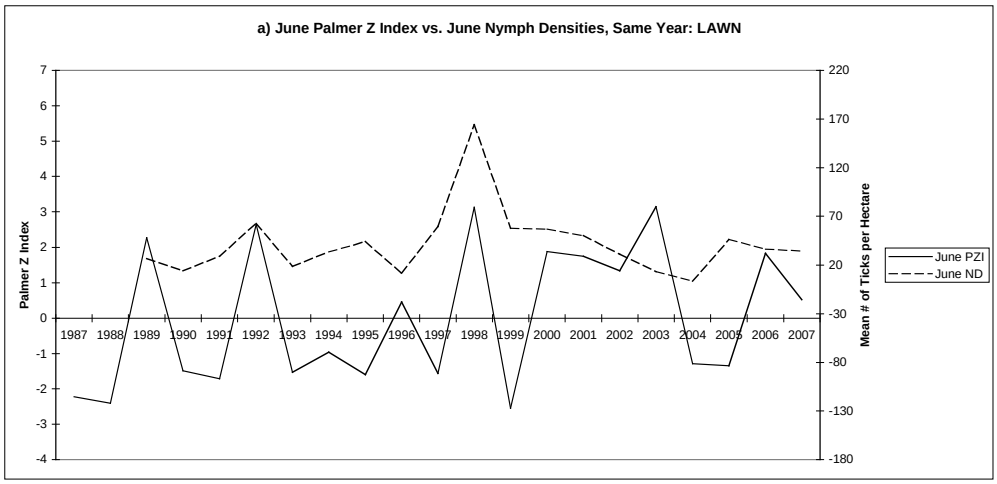
LAWN	ERI (% infection rate x mean # nymphs per hectare)		
Moisture conditions	Same Year	Next Year	Two Years On
May	--	--	**0.455**** $_{H}$ (r_s = 0.451*$_{H}$)
June	0.387*$_{Z}$ (r_s = 0.247$_{H}$ NS)	-0.379*$_{Z}$ (r_s = **-0.525****$_{Z}$)	--
July	--	--	--
August	--	--	--

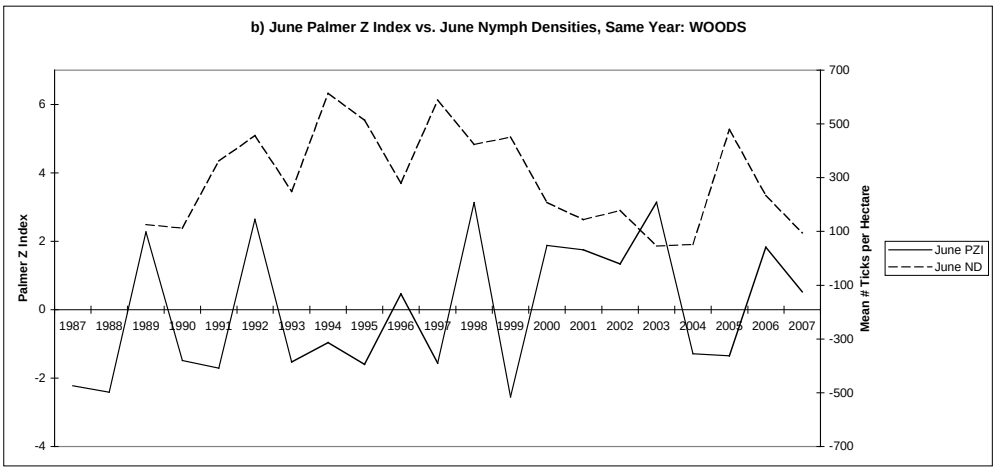
-- results were not statistically significant ($p > 0.1$)
* r values are statistically significant at $p \leq 0.10$
** r values (in bold) are statistically significant at $p \leq 0.05$
Correlations are Pearson's correlation coefficients, unless otherwise indicated
r_s = Spearman's correlation coefficients; NS = not statistically significant at $p > 0.10$
Z = PZI, or Palmer Z Index; H = PHDI, or Palmer Hydrological Drought Index

Table 5. Mean Woods moisture conditions (PZI and PHDI) vs. ERI.

WOODS	ERI (% infection rate x mean # nymphs per hectare)		
Moisture conditions	Same Year	Next Year	Two Years On
May	--	--	**0.441**** $_{H}$ (r_s = **0.537****$_{H}$)
June	--	--	--
July	--	--	0.154$_{H}$ NS (r_s = 0.403*$_{H}$)
August	--	--	--

-- results were not statistically significant ($p > 0.1$)
* r values are statistically significant at $p \leq 0.10$
** r values (in bold) are statistically significant at $p \leq 0.05$
Correlations are Pearson's correlation coefficients, unless otherwise indicated
r_s = Spearman's correlation coefficients; NS = not statistically significant at $p > 0.10$
Z = PZI, or Palmer Z Index; H = PHDI, or Palmer Hydrological Drought Index





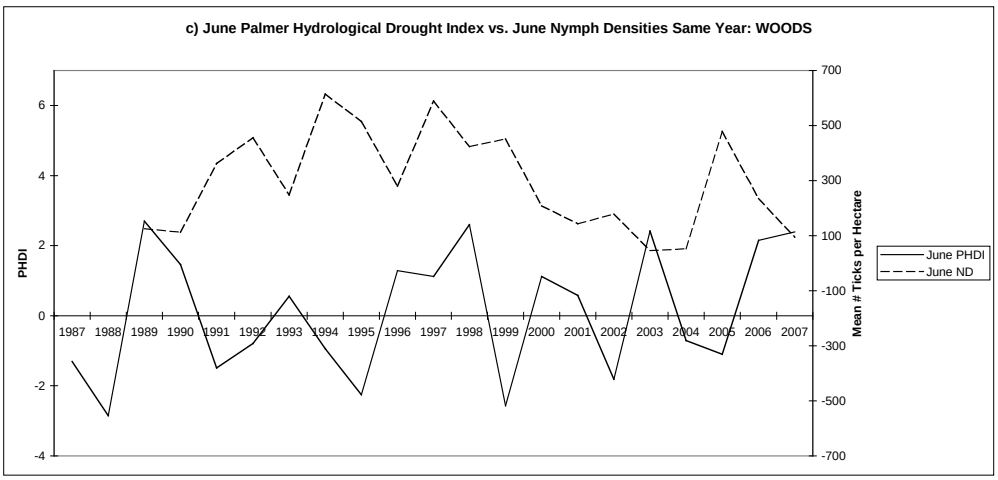


Figure 3. June moisture conditions a) correlated positively with June nymph densities for Lawn sites ($p < 0.10$), but negatively with June moisture conditions for Woods sites b) and c) (b: $p < 0.10$, c: $p < 0.05$). [PZI = Palmer Z Index; PHDI = Palmer Hydrological Drought Index; June ND = June mean nymph densities.]

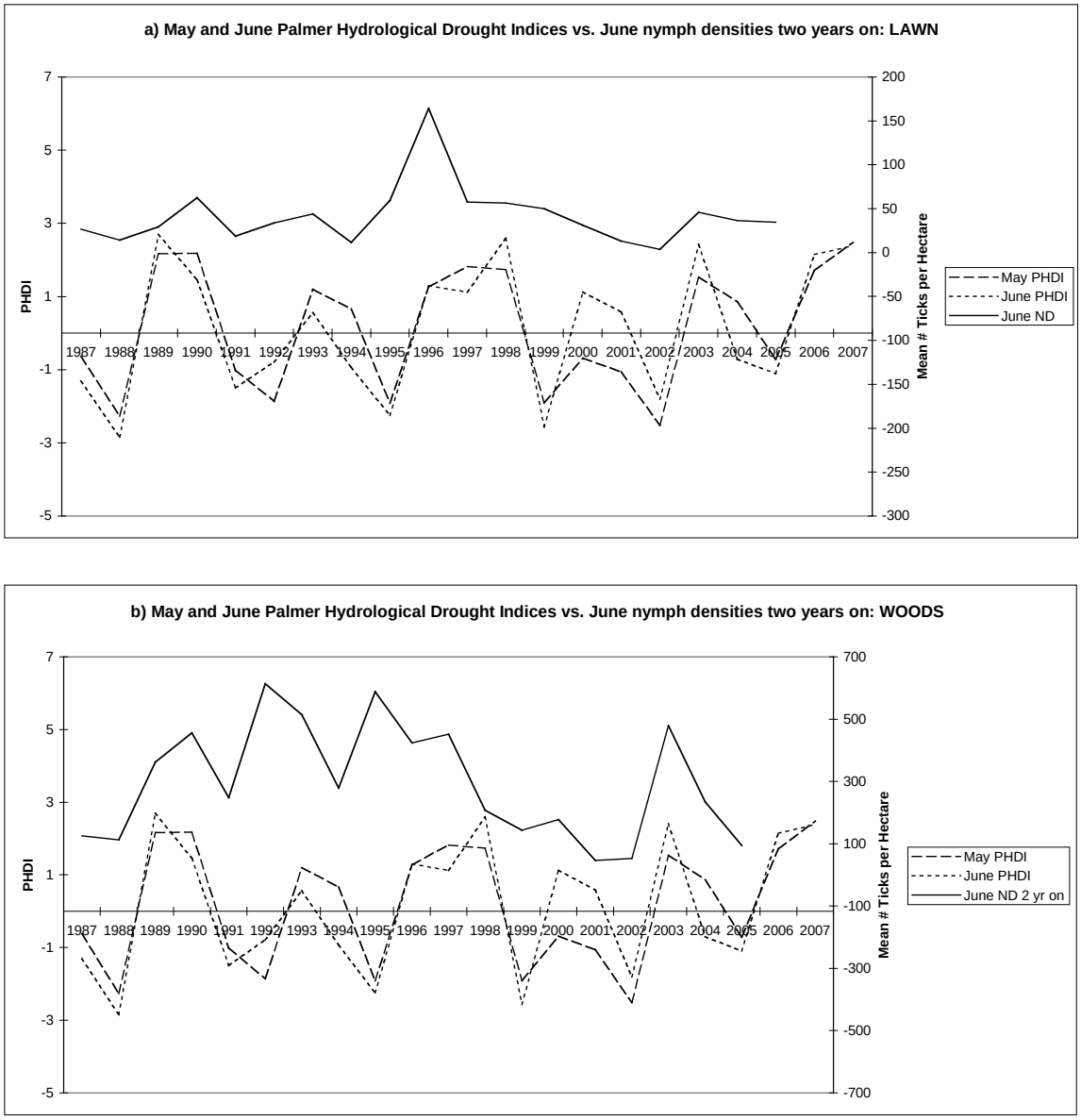


Figure 4. June moisture conditions correlated positively with a) Lawn June nymph densities two years on (May: $p < 0.05$; June: $p < 0.10$), and with b) Woods June nymph densities two years on ($p < 0.10$). [PHDI = Palmer Hydrological Drought Index; June ND = June mean nymph densities.]

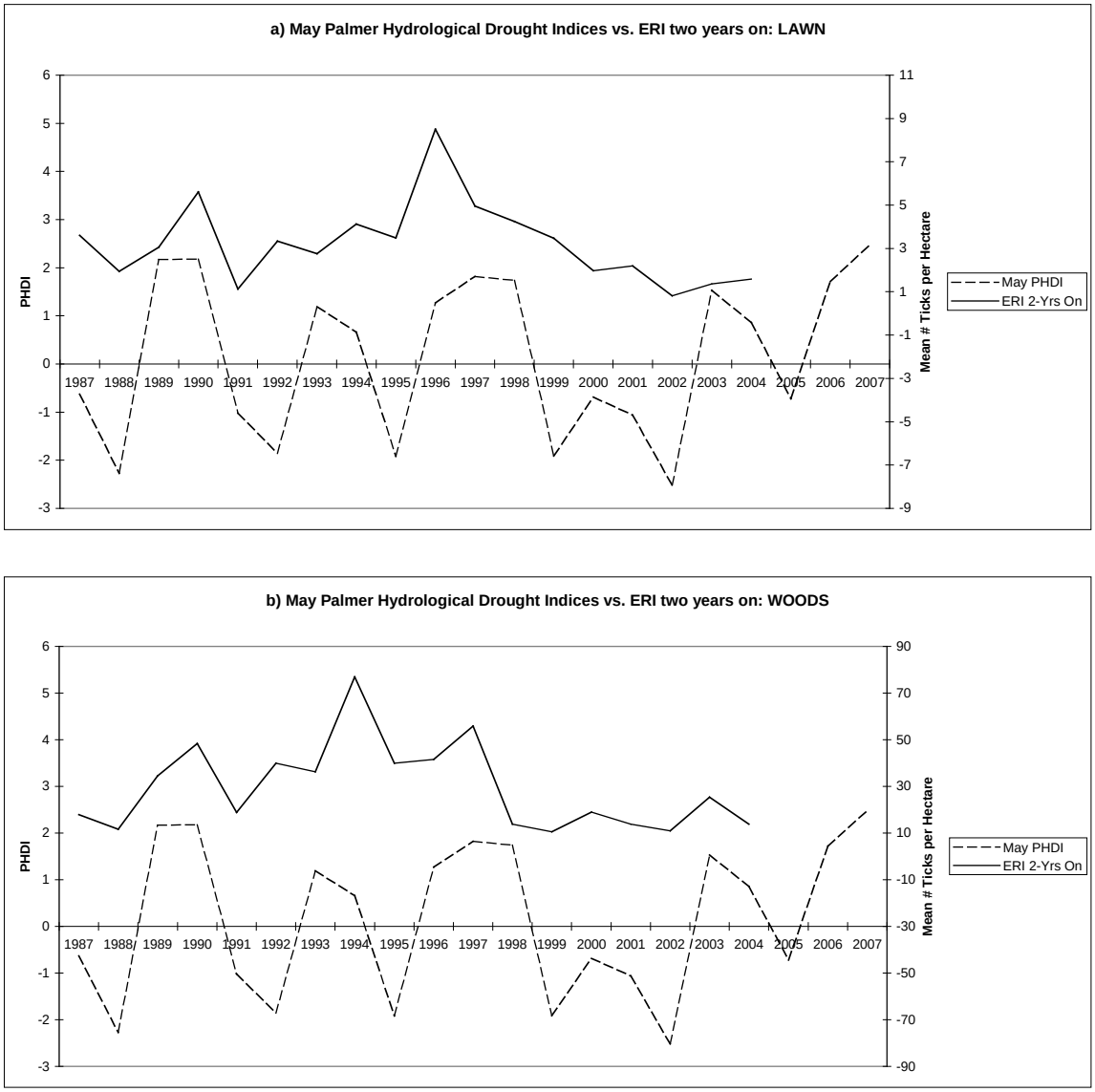


Figure 5. June moisture conditions correlated positively with a) Lawn ERI two years on (May: $p < 0.05$; June: $p < 0.10$), and with b) Woods ERI two years on ($p < 0.10$). [ERI = Entomological Risk Index; PHDI = Palmer Hydrological Drought Index; June ND = June mean nymph densities.]

Discussion

Though the correlations were moderate, the data did appear to support Subak's[11] hypothesis that moisture and drought conditions affect nymph tick survival in northeastern states. Subak suggested that 1) nymph survival is enhanced under more wet conditions while reduced under drought conditions, and 2) the effect on nymph survival is not seen until June two summers on, in the next generation of nymphs. The two-year time lag apparently results from the vulnerability of the original nymphs to dry conditions after they have successfully found a host.[11] This arises because ticks lose their ability to regulate their body moisture by either evaporation or water uptake once they begin to feed.[28, 29] In other words, nymphs that have started to feed over the course of the summer will be less likely to survive the summer if conditions are drier than normal (Year 0), leading to fewer adults to lay eggs in the spring of the following year (One Year On), leading to fewer larvae hatching, and thus fewer nymphs the year after that (Two Years On: refer to Figure 2). The reverse would be true for summers that are wetter than normal. This pattern was supported by the variations observed in nymph densities in the current study.

The current study therefore also supported Subak's[11] findings, that Lyme disease incidence is linked to June moisture conditions two years previously. Subak found that if June moisture levels are higher than normal, Lyme disease incidence is higher two years later. This would make sense if June nymph densities were also higher two summers later, and also if the ERI was higher two summers later (given the observation that Lyme disease incidence correlates with annual fluctuations in population densities of *I.*

scapularis infected with *B. burgdorferi* [12]). Both were found to be the case in the current study, thus providing an explanation for Subak's observations.

Unlike Subak[11], McCabe and Bunnell[22] were also able to find a correlation between moisture conditions and same year incidence of Lyme disease in the northeastern United States (though note that MacCabe and Bunnell used summer precipitation measures, while Subak used Palmer Hydrological Drought Indices). McCabe and Bunnell hypothesize that this is due to an increase in nymph activity and survival under wetter conditions in late spring and early summer. In contrast, Subak's failure to find same-year positive correlations led her to conclude that moisture conditions may not in fact play an important role in nymph survival in early summer, before nymphs have started to feed. Both these authors' hypotheses are consistent with the current study findings. Nymph densities did increase somewhat in Lawn sites in wetter Junes and decrease in drier ones. Lawns are more vulnerable to drying out than Woods, which may explain the fact that this pattern was not observed in Woods sites. Thus, when conditions are wetter than usual, nymph activity is picked up much more easily in Lawn sites and ERI in Lawn areas increases.

Finally, the fact that Subak failed to find a one-year lag between June moisture levels and Lyme disease suggests that moisture conditions do not significantly affect larval survival (these would lead to nymph populations one year later). However, the current study found that nymph densities in Wood sites did in fact tend to drop in the early summer months the year after a wetter summer, and vice versa. Why this should be the case in Woods but not Lawn sites is not clear. Perhaps May flooding in woodland habitats is a greater problem for eggs survival than in grass habitats.[30]

The fact that the correlations found were not terribly strong is surprising, given Subak's[11] much more robust correlations with PHDI and Lyme disease incidence. If anything, the fact that the current study was addressing nymph densities more directly, rather than nymph densities based on Lyme disease incidence (Subak), one would expect any associations between the two to be stronger than in Subak's study. It is likely, though, that there is a lot of noise in the data. For one, nymph densities were measured by counting the number of nymphs that crawled onto the piece of flannel used in "dragging". Even if there are a large number of nymphs in the vegetation, the count may not be indicative of actual nymph densities for that particular day if they are less active than normal. For example, on a couple of very wet nymph-sample days, nymph counts were considerably below average for that time of the month. Nymph collection is also not feasible on days when it is raining hard, and occasionally this condition persisted for many days at a time. This could lead to lower mean nymph densities for that particular month.

Other factors not considered in this study that may have affected summer nymph densities include moisture conditions during the winter months, and variations from the normal seasonal changes in temperature. So far, some researchers[11, 22] have failed to find a link between winter temperatures and same year Lyme disease incidence (though see McEnroe[18, 19, 31]). It remains to be seen whether winter temperature variations do impact larval numbers over the winter, or nymph numbers the following spring. With regards to moisture conditions during the winter months, ticks spend the winter months in quiescence and dormancy, and they do best under humid microclimate conditions, such as under decomposing plant matter.[29] This suggests that winter moisture conditions

would have an impact on summer nymph densities, since the degree of soil humidity affects their survival.[29] The availability of suitable ground cover may also have an impact on summer nymph densities[32], as it is less plentiful under more dry conditions.[28, 33, 34]

Another factor influencing nymph densities that could not be directly considered in this study is the effect of moisture conditions on rodent host populations. For example, smaller forest patches can lead to a lower prevalence of nymphs on mice.[35, 36] In addition, habitats that are diverse in different types of potential host species (such as squirrels and shrews) appear to dilute nymph density on key host species (such as mice)[37, 38], though it is not clear what impact this would have on overall nymph density.

One current hypothesis regarding variation in the incidence Lyme disease in the northeastern states is that such variation reflects periodic changes in acorn production in oak forests. Summers with an abundance of acorns tend to be followed by an explosion in populations of white-footed mice (*Peromyscus leucopus*) that feed primarily on acorns.[39] Moist conditions lead to more available food to sustain a higher rodent population through the winter[30, 40], providing more opportunity for larvae to feed and leading to more nymphs the following spring. In addition, it is possible that a drier July and August may lead to smaller rodent host populations (e.g., white-footed mice[41]), and as a result, higher densities of nymphs per host animal. This might lead to a higher proportion of infected nymphs in years with drier than normal summers than in wetter summers. This in turn, could lead to a higher incidence of Lyme disease the following summer even if nymph densities are not appreciably higher.

With respect to white-footed mice however, it is worth noting that Lyme disease-infected ticks are also found in forests not dominated by oaks, as well as in regions

without forests. In addition, there is some evidence that the acorn theory may only partially explain the observed variability in Lyme disease incidence, since one study found that peaks in the county incidence of Lyme disease failed to follow peaks in local acorn production in central Massachusetts.[42] Acorn production varies depending on the species of oak and environmental conditions. Though variation in host animal populations explain some of the variation in nymph densities observed, climate factors may in fact be playing a more direct role on tick survival.[18, 19, 31]

It is interesting that associations found between moisture levels and nymph densities depended on whether PHDI or PZI were used as measures of moisture conditions. The findings suggest long-term cumulative moist or drought conditions that have had a more substantial impact on vegetation (PDHI) are more likely to have an impact on nymph survival that summer – and thus nymph densities two years on – than more short-term conditions of drought and wetness (PZI). At the same time, not surprisingly, short-term conditions seem to have a more immediate affect on nymph densities at the time of nymph collection.

Conclusion

The current study findings support the hypothesis that late spring and early summer moisture and drought conditions can impact nymph survival, the effect of which is not apparent until the early summer two years later with the next generation of nymphs. In other words, a wetter than average May and June tends to lead to a higher density of *I. scapularis* tick nymphs two years later, especially in woodland-field edges, while a drier May and June has the reverse effect. The same pattern emerged with the ERI data. This

suggest that people who own properties in or who engage in activities in woodland habitats and along the borders of such habitats, are probably more at risk in picking up *B. burgdorferi* infected ticks in May and June, when the summer two years previously was wetter than normal.

The data also suggested that people increasing their activities in woodland-field edges on non-rainy June days are also probably more likely to pick up infected ticks if the spring and early summer has been wetter than normal. Finally, there might be short-term flooding effect in woodland habitats in May and June that affects the survival of larval ticks, leading to fewer nymphs in June of the following year. However, no similar pattern emerged with the ERI data. Thus, the incidence of Lyme disease appears to linked to variation in moisture conditions in previous summers. This supports observations in earlier studies. Not only are Junes that are wetter than average likely to increase the incidence of Lyme disease in the same year, wetter Junes are also likely to increase the incidence of Lyme disease two summers later.

Appendix

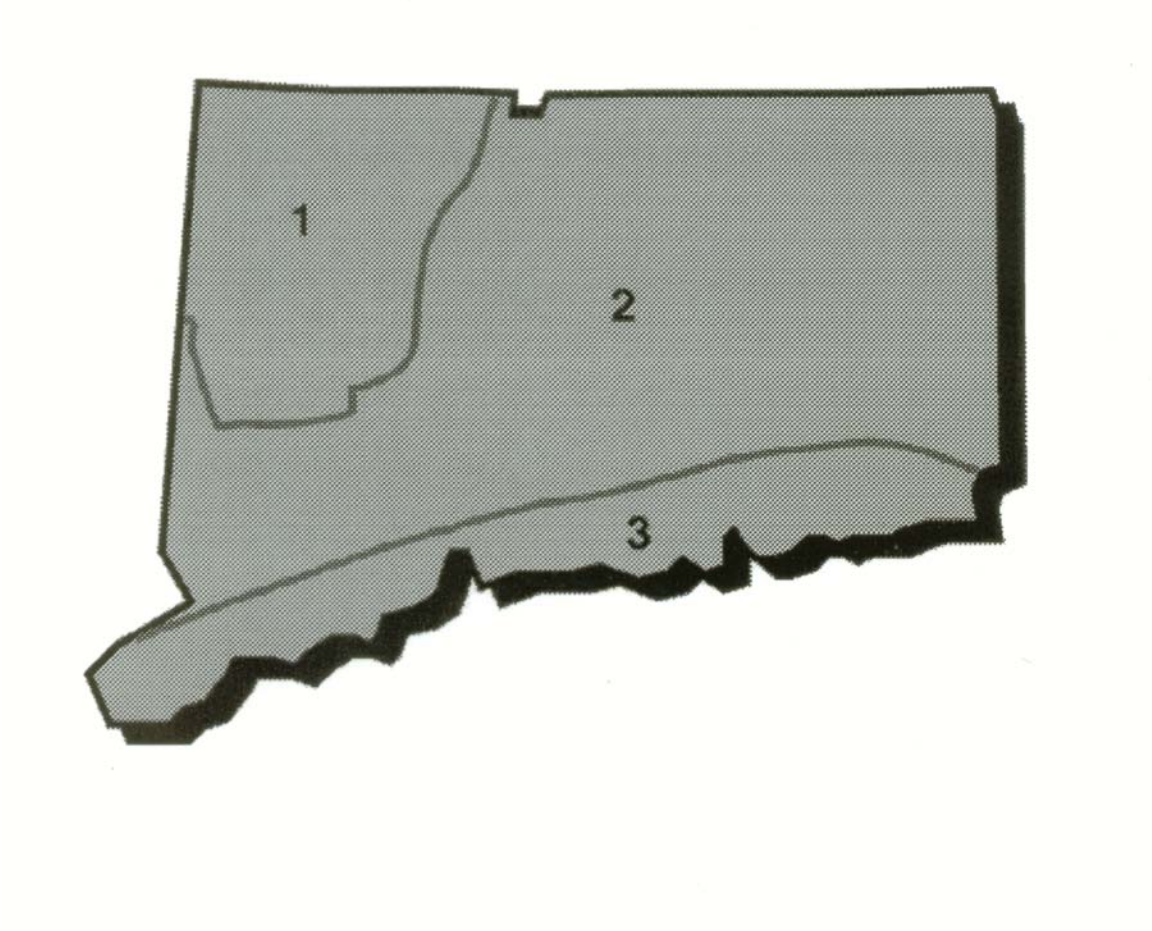


Figure A1. There are three climatic divisions in Connecticut. NOAA reported climate data was for the southern region of Connecticut (Division 3).

Table A1. Connecticut Palmer "Z" Index (PZI) Division 3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
603071987	1.99	-3.43	0.19	1.9	-1.9	-2.22	-2.81	-0.23	0.92	-0.29	-0.9	-1.57
603071988	-0.63	1.03	-1.28	-2.22	-0.8	-2.41	2.55	-1.87	-1.12	-0.15	3.75	-1.99
603071989	-2.01	-0.24	-0.57	0.51	6.04	2.27	0.91	3.15	0.53	4.95	-0.13	-2.54
603071990	0.78	-1.12	-1.98	0.98	2.61	-1.49	-0.32	1.96	-1.28	2.66	-1.54	0.58
603071991	-0.37	-1.69	0.24	-0.76	-0.65	-1.71	-1	3.58	1.04	-1.11	-0.91	0.23
603071992	-0.94	-1.45	-0.27	-1.73	-1.29	2.64	0.99	3.6	2.21	-0.37	1.67	1.44
603071993	-1.03	-0.28	2.67	0.05	-2.7	-1.53	-2.56	-2.82	1.9	0.57	-1.45	1.1
603071994	1.69	-0.11	2.58	-1.77	-0.48	-0.96	-1.88	1.04	0.01	-2.31	-0.72	0.22
603071995	-0.43	0.26	-2.65	-0.78	-0.41	-1.6	-2.18	-3.44	-0.37	1.81	0.42	-1.13
603071996	1.43	-0.14	-0.48	3.93	-0.56	0.46	2.86	-1.18	2.18	5	-0.23	2.75
603071997	-0.02	-1.33	1.33	-0.84	-0.3	-1.56	-0.55	0.46	-2.37	-1.85	0.07	-0.3
603071998	0.93	1.15	0.96	1.39	1.77	3.13	-2.04	-2.7	-1.74	-0.74	-2.7	-3.4
603071999	2.88	1.45	-0.61	-2.38	0.14	-2.55	-3.59	-0.42	4.57	1.16	-1.16	-0.75
603072000	-0.55	-1.41	0.68	1.02	0.13	1.88	2.61	2.4	1.39	-2.24	0	-0.33
603072001	-0.65	-1.4	3.75	-2.6	-0.84	1.75	-0.4	0.76	-0.43	-2.22	-3.72	-2.63
603072002	-1.92	-2.81	-0.16	-0.55	1.01	1.34	-2.08	-1.37	1.69	1.01	1.17	1.21
603072003	-1.36	1.48	1.16	0.11	0.87	3.14	-0.36	0.32	0.84	1.5	-1.11	0.64
603072004	-1.52	-0.7	-0.26	2.43	-0.92	-1.29	1.34	1.74	3.66	-1.11	0.22	-0.05
603072005	0.67	-0.53	-0.42	-0.32	-1.16	-1.35	-1.39	-2.82	-2.49	7	-0.66	-0.16
603072006	1.52	-0.97	-3.47	3.47	2.05	1.83	0.16	4.48	-0.51	3.75	1.57	-1.39
603072007	0.59	-2.39	1.42	6	-2.99	0.52	-0.49	-1.21	-2.3	-1.97	-2.1	0.29
603072008	-1.5	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99

Values in 1st column: 6 = CT; 03 = climate division 3 (southern CT); 07 = Palmer Z Index data; Year of data. From NOAA. Last Modified 2/14/08. -99.99 values = PZI data not available yet.

Table A2. Connecticut Palmer Hydrological Drought Index (PHDI) Division 3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
603061987	1.74	-1.14	-0.96	0.69	-0.63	-1.31	-2.11	-1.97	-1.46	-1.4	-1.56	-1.92
603061988	-1.93	-1.39	-1.67	-2.24	-2.27	-2.85	-1.7	-2.15	-2.3	-2.12	-0.65	-1.24
603061989	-1.78	-1.68	-1.7	-1.35	2.17	2.7	2.73	3.49	3.31	4.62	4.1	2.83
603061990	2.8	2.14	1.26	1.46	2.18	1.46	1.2	1.73	1.12	1.89	1.19	1.26
603061991	1	-0.89	-0.71	-0.89	-1.02	-1.49	-1.66	1.19	1.42	0.9	-0.64	-0.49
603061992	-0.76	-1.16	-1.13	-1.59	-1.86	-0.79	1.12	2.2	2.72	2.31	2.63	2.84
603061993	2.2	1.88	2.58	2.33	1.19	0.56	-2.03	-2.76	-1.85	-1.47	-1.8	-1.25
603061994	-0.56	0.9	1.67	0.91	0.66	-0.94	-1.47	-0.97	-0.87	-1.54	-1.63	-1.39
603061995	-1.39	-1.16	-1.92	-1.99	-1.92	-2.25	-2.75	-3.61	-3.36	-2.41	-2.02	-2.19
603061996	-1.49	-1.38	-1.4	1.62	1.27	1.29	2.11	1.5	2.07	3.53	3.09	3.68
603061997	3.3	2.52	2.7	2.14	1.82	1.12	0.82	0.89	-1.4	-1.87	-1.66	-1.59
603061998	-1.11	-0.62	0.91	1.28	1.74	2.6	1.65	0.58	-1.93	-1.98	-2.68	-3.53
603061999	-2.21	-1.5	-1.55	-2.18	-1.91	-2.57	-3.5	-3.28	-1.42	-0.88	-1.18	-1.31
603062000	-1.36	-1.69	-1.29	-0.81	-0.69	1.12	1.87	2.48	2.69	1.66	1.49	1.23
603062001	0.88	-1.23	1.25	-0.87	-1.06	0.58	0.39	0.6	-0.14	-0.87	-2.02	-2.68
603062002	-3.05	-3.67	-3.35	-3.18	-2.52	-1.81	-2.32	-2.54	-1.71	-1.2	-0.69	1.43
603062003	0.83	1.24	1.5	1.38	1.53	2.42	2.05	1.94	2.02	2.31	1.7	1.74
603062004	1.06	0.71	0.55	1.3	0.86	-0.71	0.45	0.98	2.1	1.51	1.43	1.27
603062005	1.36	1.04	0.8	0.61	-0.72	-1.1	-1.45	-2.24	-2.84	2.33	1.87	1.63
603062006	1.96	1.44	-1.45	1.16	1.72	2.15	1.98	3.27	2.76	3.73	3.87	3.01
603062007	2.89	1.8	2.09	3.87	2.48	2.39	1.98	1.38	-1.78	-2.26	-2.72	-2.35
603062008	-2.6	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99	-99.99

Values in 1st column: 6 = CT; 03 = climate division 3 (southern CT); 06 = Palmer Hydrological Drought Index data; Year of data.
From NOAA. Last Modified 2/14/08. -99.99 values = PHDI data not available yet.

Table A3. Palmer Z Indices and Lawn mean nymph densities for May through August, over 19-21 years.

	May PZI	June PZI	July PZI	Aug PZI	May ND	June ND	July ND	Aug ND	ERI
1987	-1.9	-2.22	-2.81	-0.23	--	--	--	--	--
1988	-0.8	-2.41	2.55	-1.87	--	--	--	--	--
1989	6.04	2.27	0.91	3.15	2.65	26.66	20.88	10.46	3.6
1990	2.61	-1.49	-0.32	1.96	3.95	14.31	23.67	4.75	1.95
1991	-0.65	-1.71	-1	3.58	5.10	29.19	18.54	3.87	3.05
1992	-1.29	2.64	0.99	3.6	3.93	62.57	78.32	12.41	5.61
1993	-2.7	-1.53	-2.56	-2.82	0.53	18.71	15.50	2.67	1.13
1994	-0.48	-0.96	-1.88	1.04	5.34	33.68	32.61	11.76	3.34
1995	-0.41	-1.6	-2.18	-3.44	1.60	43.84	23.52	--	2.76
1996	-0.56	0.46	2.86	-1.18	2.13	11.76	17.64	2.13	4.12
1997	-0.3	-1.56	-0.55	0.46	11.77	59.34	40.63	14.23	3.49
1998	1.77	3.13	-2.04	-2.7	41.66	164.16	103.33	12.5	8.51
1999	0.14	-2.55	-3.59	-0.42	17.5	57.5	30.83	2.5	4.96
2000	0.13	1.88	2.61	2.4	25.28	56.59	65.02	4.81	4.25
2001	-0.84	1.75	-0.4	0.76	1.20	49.96	24.68	3.61	3.47
2002	1.01	1.34	-2.08	-1.37	10.83	31.30	12.04	2.40	1.97
2003	0.87	3.14	-0.36	0.32	--	13.24	3.61	--	2.2
2004	-0.92	-1.29	1.34	1.74	--	3.61	14.44	--	0.81
2005	-1.16	-1.35	-1.39	-2.82	--	46.05	29.56	7.39	1.37
2006	2.05	1.83	0.16	4.48	6.82	36.38	14.78	2.27	1.59
2007	-2.99	0.52	-0.49	-1.21	--	34.68	17.05	--	--

PZI = Palmer Z Index; ND = nymph densities (mean # ticks per hectare); ERI = Entomologic Risk Index.
-- No data collected

Table A4. Palmer Z Indices and Woods mean nymph densities for May through August, over 19-21 years.

	May PZI	June PZI	July PZI	Aug PZI	May ND	June ND	July ND	Aug ND	ERI
1987	-1.9	-2.22	-2.81	-0.23	--	--	--	--	--
1988	-0.8	-2.41	2.55	-1.87	--	--	--	--	--
1989	6.04	2.27	0.91	3.15	5.28	125.79	116.40	34.95	17.9
1990	2.61	-1.49	-0.32	1.96	36.55	112.24	83.57	10.55	11.6
1991	-0.65	-1.71	-1	3.58	73.73	362.15	130.83	37.25	34.5
1992	-1.29	2.64	0.99	3.6	121.13	456.02	247.50	75.51	48.3
1993	-2.7	-1.53	-2.56	-2.82	48.0	248.49	116.71	23.53	18.9
1994	-0.48	-0.96	-1.88	1.04	82.26	614.18	279.43	139.00	40
1995	-0.41	-1.6	-2.18	-3.44	114.89	514.89	201.41	--	36.3
1996	-0.56	0.46	2.86	-1.18	25.53	279.43	148.93	7.09	76.9
1997	-0.3	-1.56	-0.55	0.46	234.27	588.65	307.80	102.12	39.9
1998	1.77	3.13	-2.04	-2.7	243.97	424.11	288.41	82.26	41.5
1999	0.14	-2.55	-3.59	-0.42	241.34	451.44	193.07	45.42	55.8
2000	0.13	1.88	2.61	2.4	134.35	207.63	122.13	16.79	13.8
2001	-0.84	1.75	-0.4	0.76	5.925	143.70	125.92	29.62	10.6
2002	1.01	1.34	-2.08	-1.37	124.44	177.77	59.25	--	18.96
2003	0.87	3.14	-0.36	0.32	--	45.80	35.23	--	13.78
2004	-0.92	-1.29	1.34	1.74	2.96	51.85	5.92	--	10.97
2005	-1.16	-1.35	-1.39	-2.82	--	478.97	218.14	101.16	25.36
2006	2.05	1.83	0.16	4.48	211.82	233.95	91.68	18.96	13.78
2007	-2.99	0.52	-0.49	-1.21	--	94.84	72.71	--	--

PZI = Palmer Z Index; ND = nymph densities (mean # ticks per hectare); ERI = Entomologic Risk Index.
-- No data collected

Table A5. Palmer Hydrological Drought Indices and Lawn mean nymph densities for May through August, over 19-21 years.

	May PHDI	June PHDI	July PHDI	Aug PHDI	May ND	June ND	July ND	Aug ND	ERI
1987	-0.63	-1.31	-2.11	-1.97	--	--	--	--	--
1988	-2.27	-2.85	-1.7	-2.15	--	--	--	--	--
1989	2.17	2.7	2.73	3.49	2.65	26.66	20.88	10.46	3.6
1990	2.18	1.46	1.2	1.73	3.95	14.31	23.67	4.75	1.95
1991	-1.02	-1.49	-1.66	1.19	5.10	29.19	18.54	3.87	3.05
1992	-1.86	-0.79	1.12	2.2	3.93	62.57	78.32	12.41	5.61
1993	1.19	0.56	-2.03	-2.76	0.53	18.71	15.50	2.67	1.13
1994	0.66	-0.94	-1.47	-0.97	5.34	33.68	32.61	11.76	3.34
1995	-1.92	-2.25	-2.75	-3.61	1.60	43.84	23.52	--	2.76
1996	1.27	1.29	2.11	1.5	2.13	11.76	17.64	2.13	4.12
1997	1.82	1.12	0.82	0.89	11.77	59.34	40.63	14.23	3.49
1998	1.74	2.6	1.65	0.58	41.66	164.16	103.33	12.5	8.51
1999	-1.91	-2.57	-3.5	-3.28	17.5	57.5	30.83	2.5	4.96
2000	-0.69	1.12	1.87	2.48	25.28	56.59	65.02	4.81	4.25
2001	-1.06	0.58	0.39	0.6	1.20	49.96	24.68	3.61	3.47
2002	-2.52	-1.81	-2.32	-2.54	10.83	31.30	12.04	2.40	1.97
2003	1.53	2.42	2.05	1.94	--	13.24	3.61	--	2.2
2004	0.86	-0.71	0.45	0.98	--	3.61	14.44	--	0.81
2005	-0.72	-1.1	-1.45	-2.24	--	46.05	29.56	7.39	1.37
2006	1.72	2.15	1.98	3.27	6.82	36.38	14.78	2.27	1.59
2007	2.48	2.39	1.98	1.38	--	34.68	17.05	--	--

PHDI = Palmer Hydrological Drought Index; ND = nymph densities (mean # ticks per hectare); ERI = Entomologic Risk Index.
-- No data collected

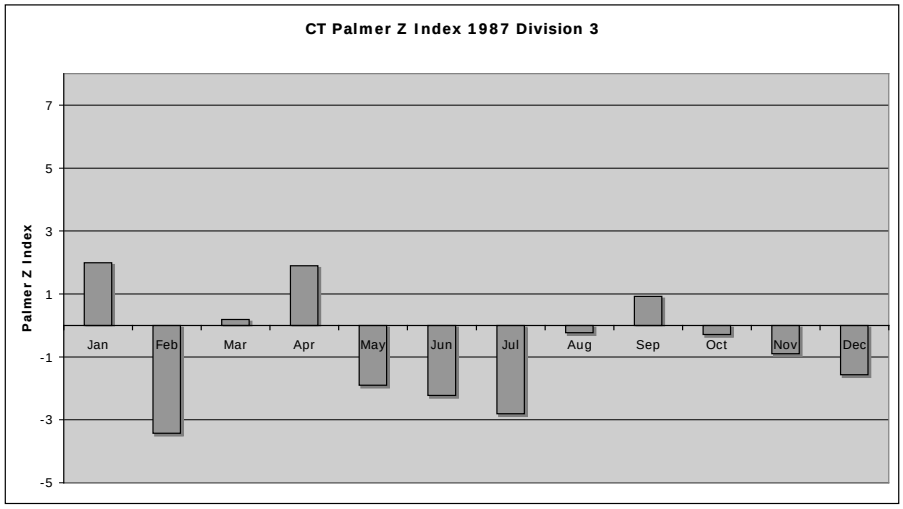
Table A6. Palmer Hydrological Drought Indices and Woods mean nymph densities for May through August, over 19-21 years.

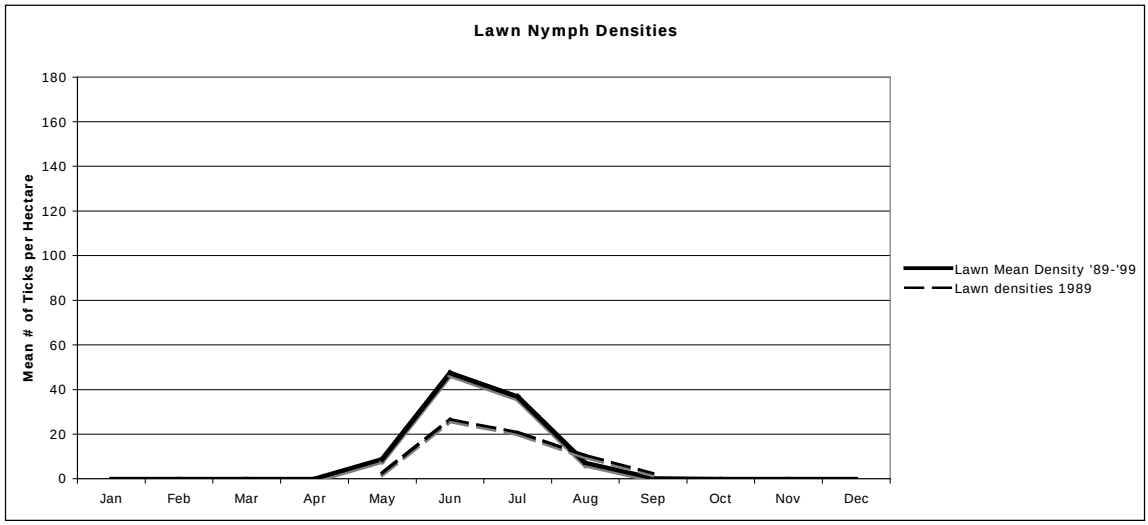
	May PHDI	June PHDI	July PHDI	Aug PHDI	May ND	June ND	July ND	Aug ND	ERI
1987	-0.63	-1.31	-2.11	-1.97	--	--	--	--	--
1988	-2.27	-2.85	-1.7	-2.15	--	--	--	--	--
1989	2.17	2.7	2.73	3.49	5.28	125.79	116.40	34.95	17.9
1990	2.18	1.46	1.2	1.73	36.55	112.24	83.57	10.55	11.6
1991	-1.02	-1.49	-1.66	1.19	73.73	362.15	130.83	37.25	34.5
1992	-1.86	-0.79	1.12	2.2	121.13	456.02	247.50	75.51	48.3
1993	1.19	0.56	-2.03	-2.76	48.0	248.49	116.71	23.53	18.9
1994	0.66	-0.94	-1.47	-0.97	82.26	614.18	279.43	139.00	40
1995	-1.92	-2.25	-2.75	-3.61	114.89	514.89	201.41	--	36.3
1996	1.27	1.29	2.11	1.5	25.53	279.43	148.93	7.09	76.9
1997	1.82	1.12	0.82	0.89	234.27	588.65	307.80	102.12	39.9
1998	1.74	2.6	1.65	0.58	243.97	424.11	288.41	82.26	41.5
1999	-1.91	-2.57	-3.5	-3.28	241.34	451.44	193.07	45.42	55.8
2000	-0.69	1.12	1.87	2.48	134.35	207.63	122.13	16.79	13.8
2001	-1.06	0.58	0.39	0.6	5.925	143.70	125.92	29.62	10.6
2002	-2.52	-1.81	-2.32	-2.54	124.44	177.77	59.25	--	18.96
2003	1.53	2.42	2.05	1.94	--	45.80	35.23	--	13.78
2004	0.86	-0.71	0.45	0.98	2.96	51.85	5.92	--	10.97
2005	-0.72	-1.1	-1.45	-2.24	--	478.97	218.14	101.16	25.36
2006	1.72	2.15	1.98	3.27	211.82	233.95	91.68	18.96	13.78
2007	2.48	2.39	1.98	1.38	--	94.84	72.71	--	--

PHDI = Palmer Hydrological Drought Index; ND = nymph densities (mean # ticks per hectare); ERI = Entomologic Risk Index.
-- No data collected

Figure A2. Palmer Z Index for 1987 and nymph densities for the summer 2 years on.

1987





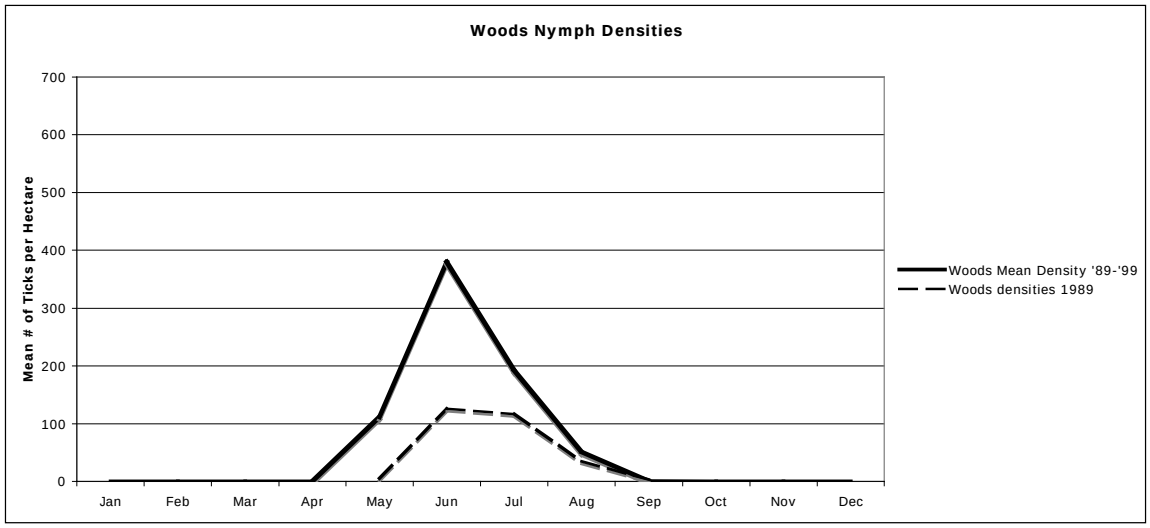
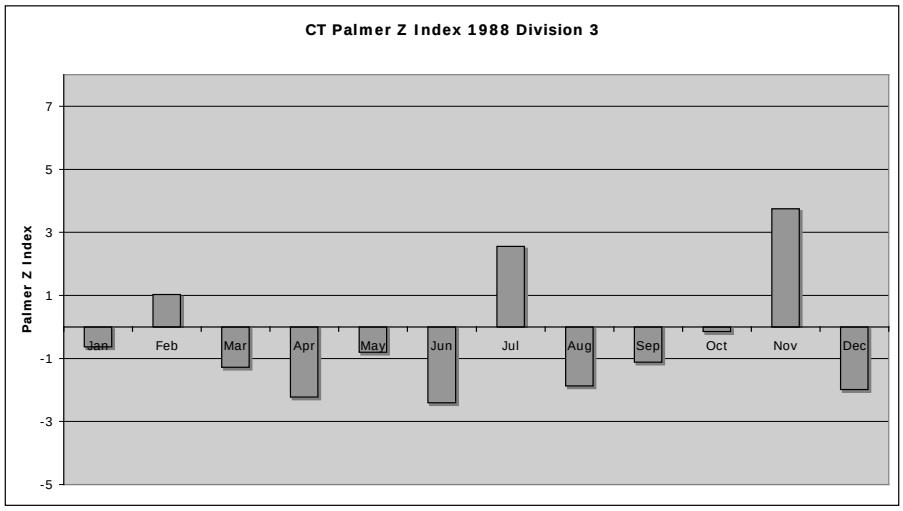
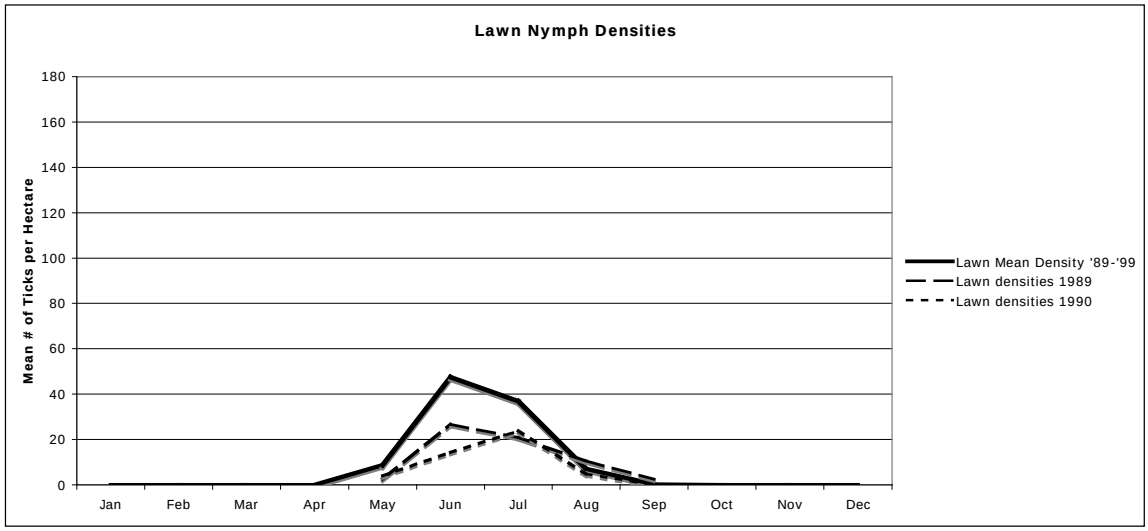


Figure A3. Palmer Z Index for 1988 and nymph densities for the three summers following.

1988





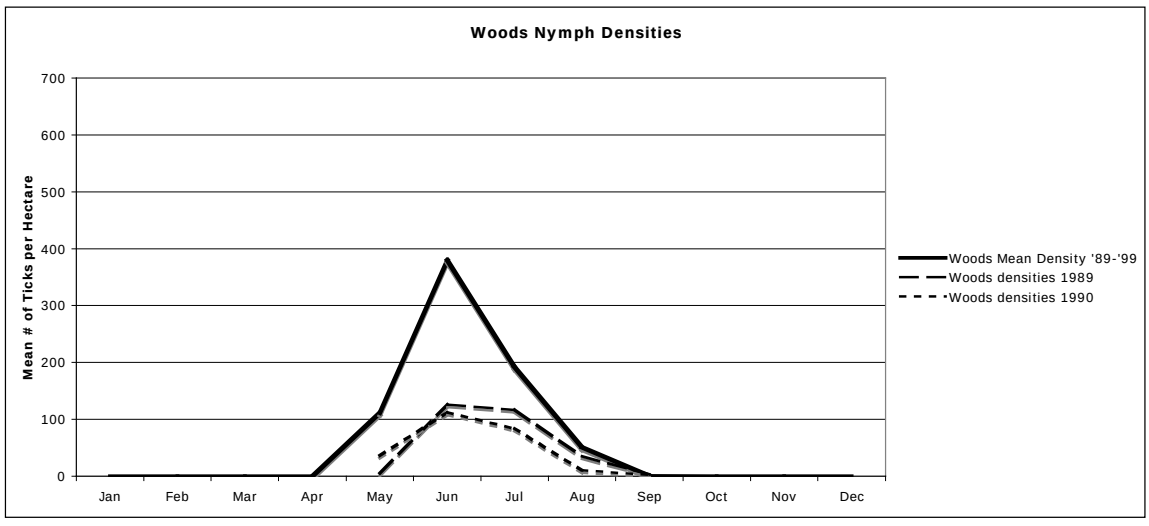
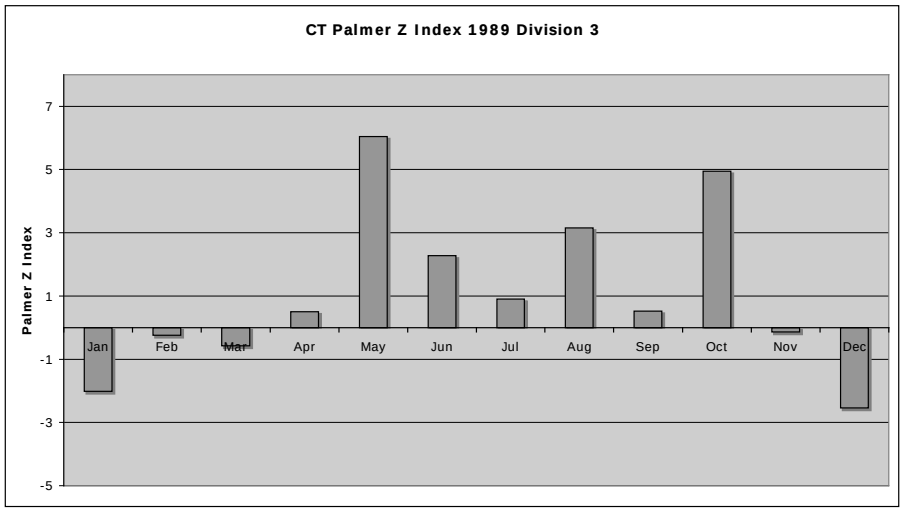
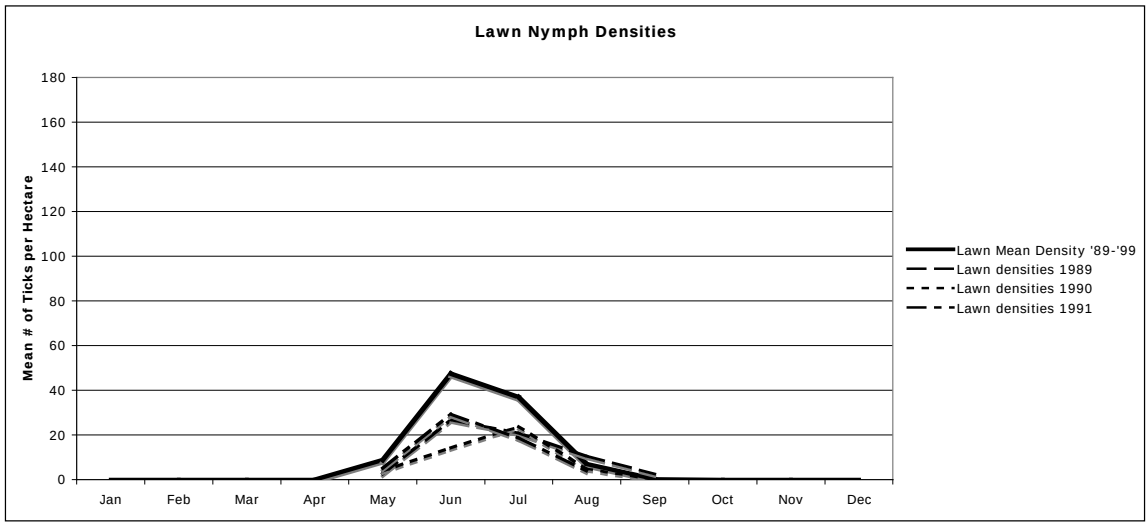


Figure A4. Palmer Z Index for 1989 and nymph densities for the three summers following.

1989





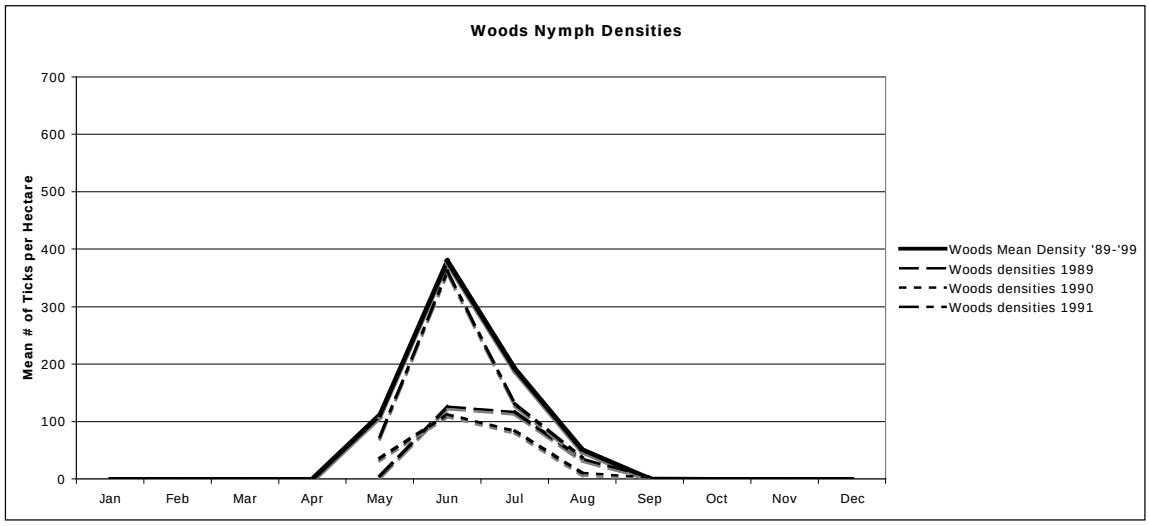
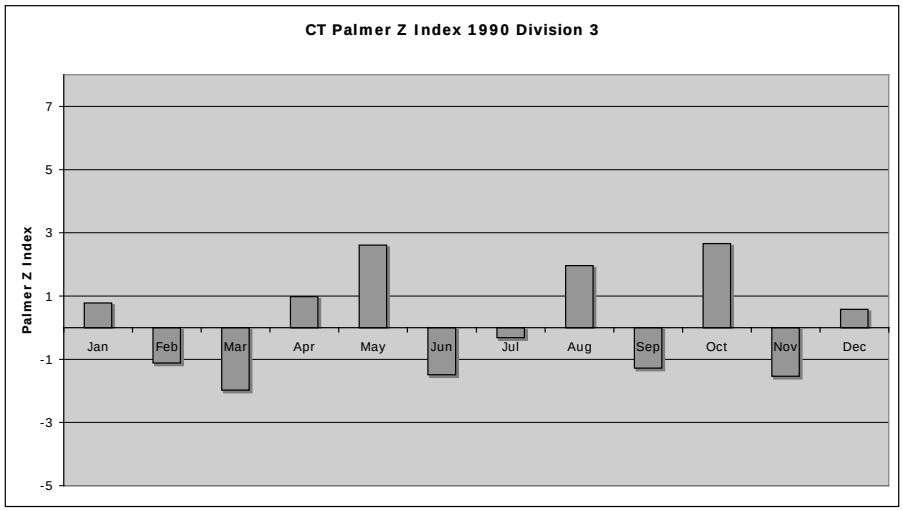
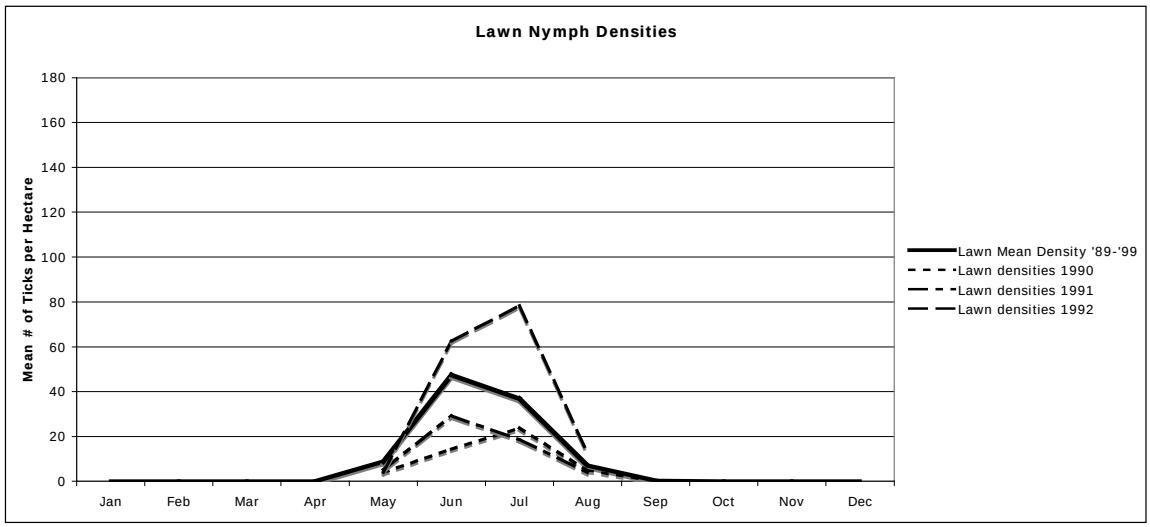


Figure A5. Palmer Z Index for 1990 and nymph densities for the three summers following.

1990





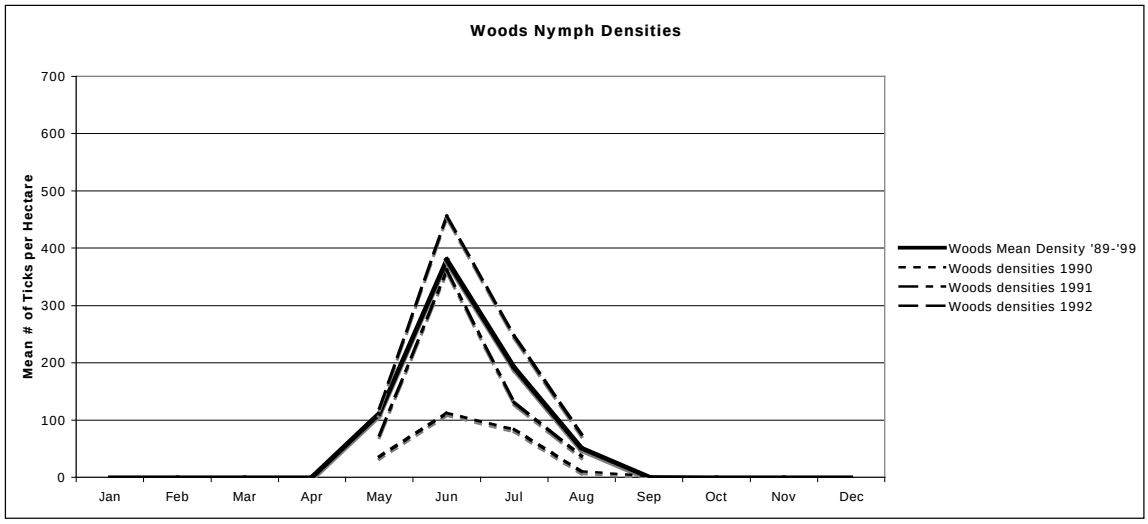
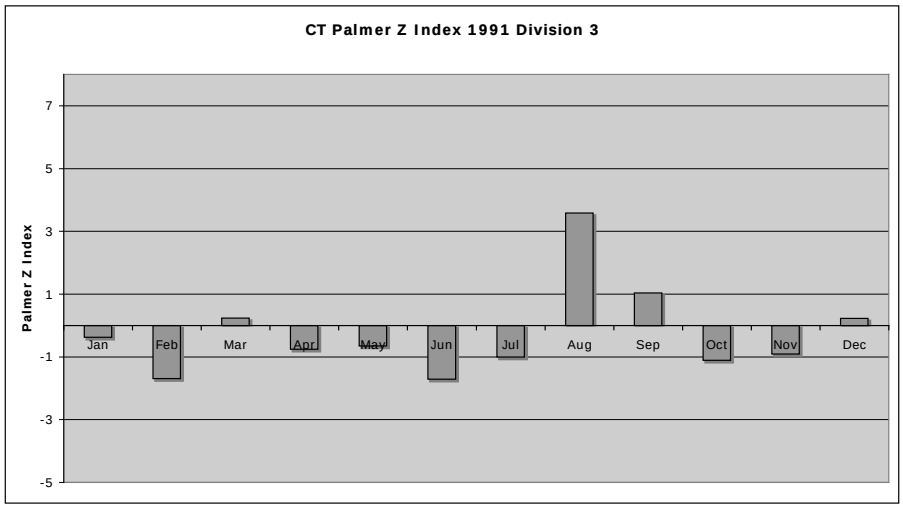
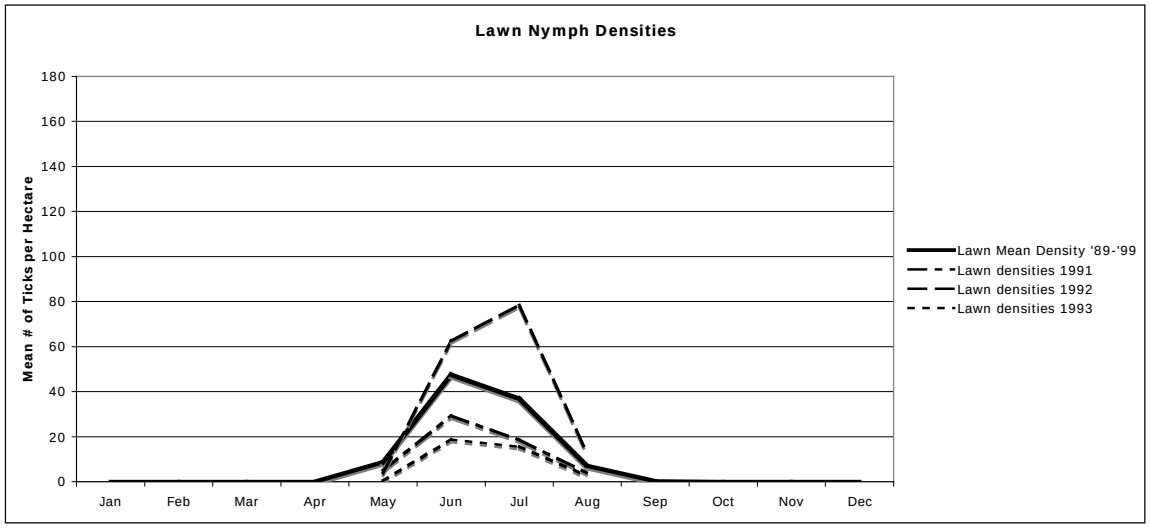


Figure A6. Palmer Z Index for 1991 and nymph densities for the three summers following.

1991





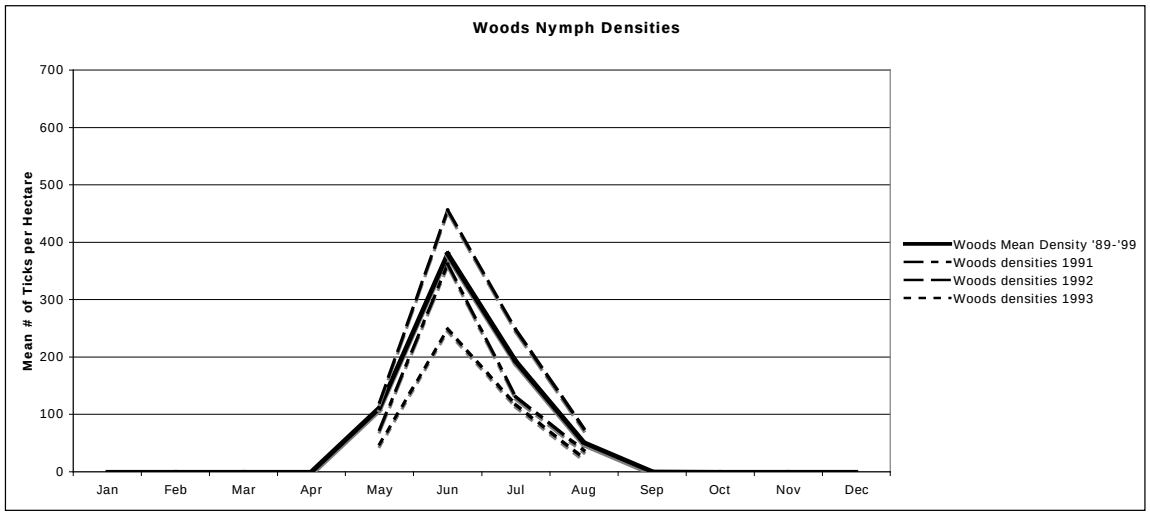
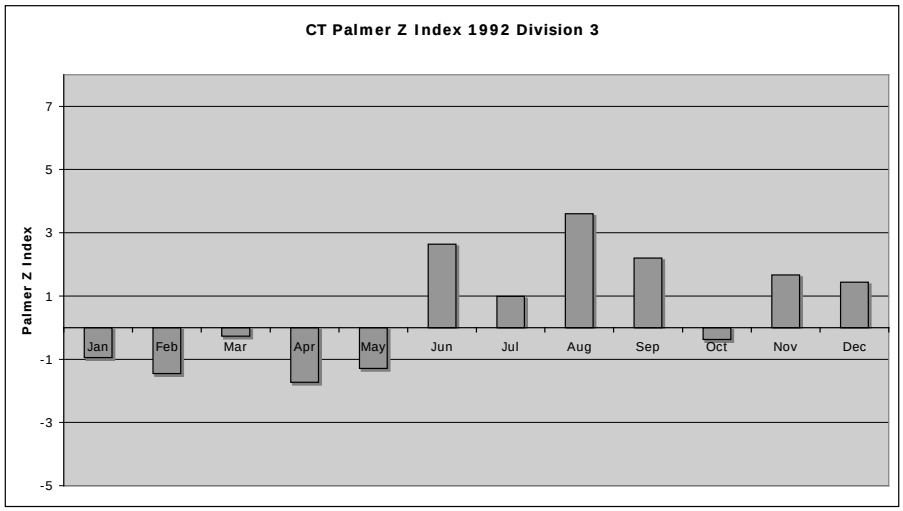
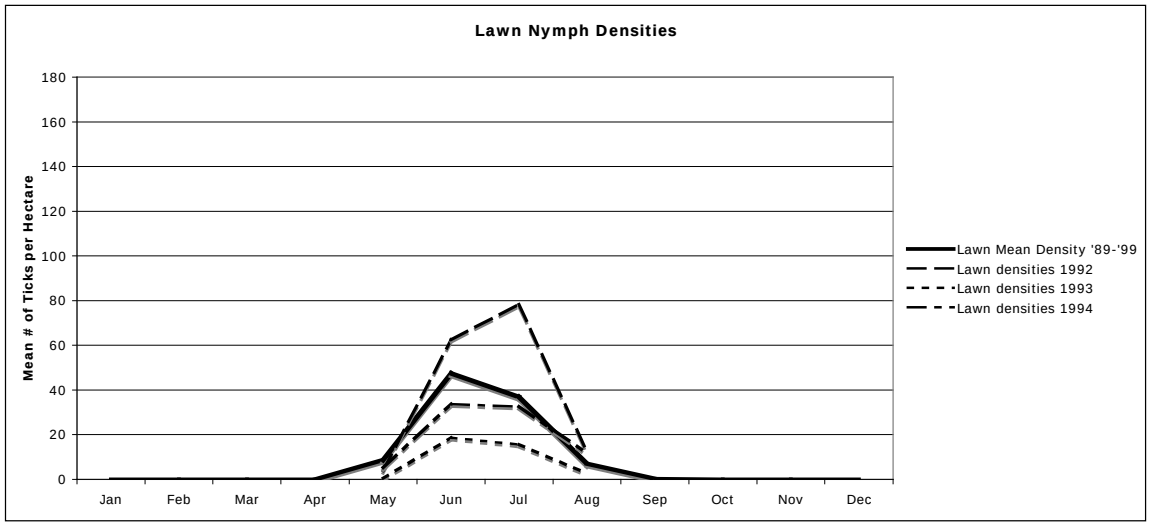


Figure A7. Palmer Z Index for 1992 and nymph densities for the three summers following.

1992





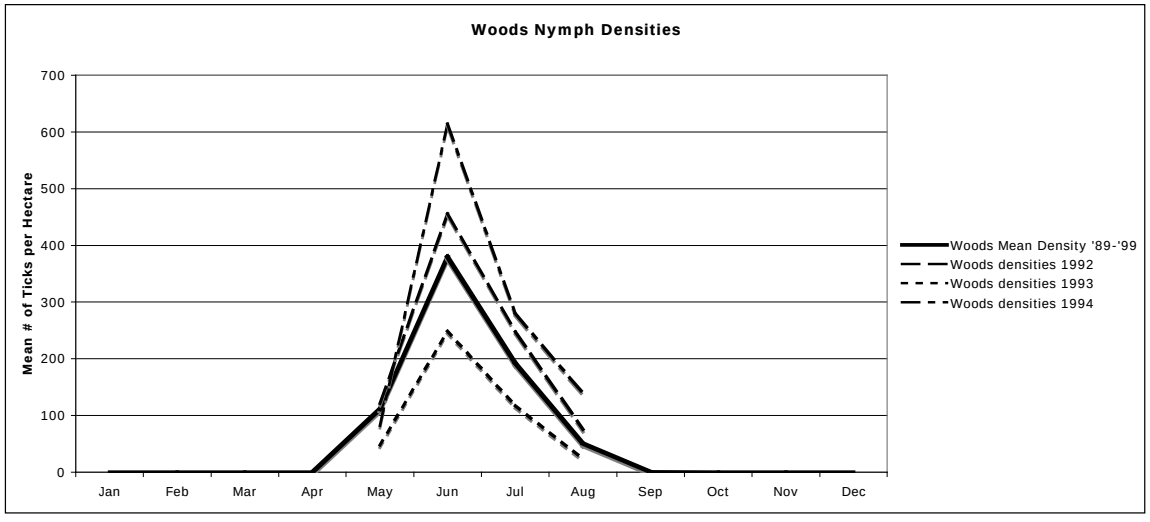
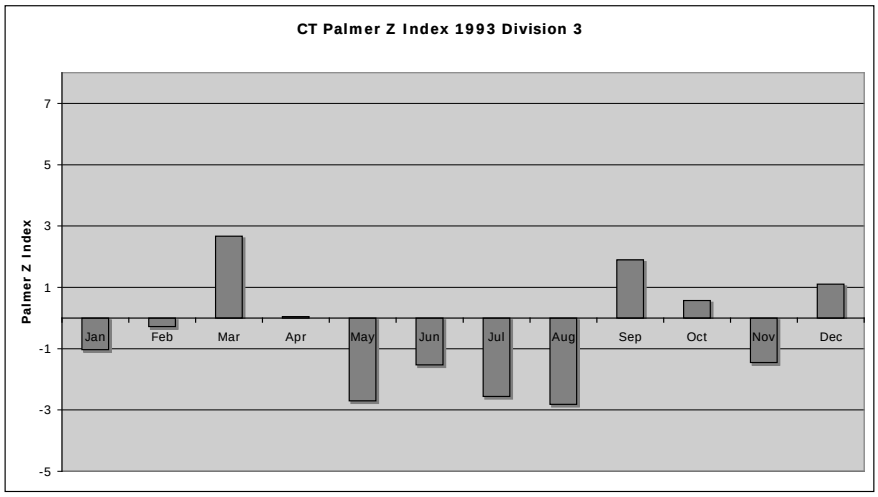
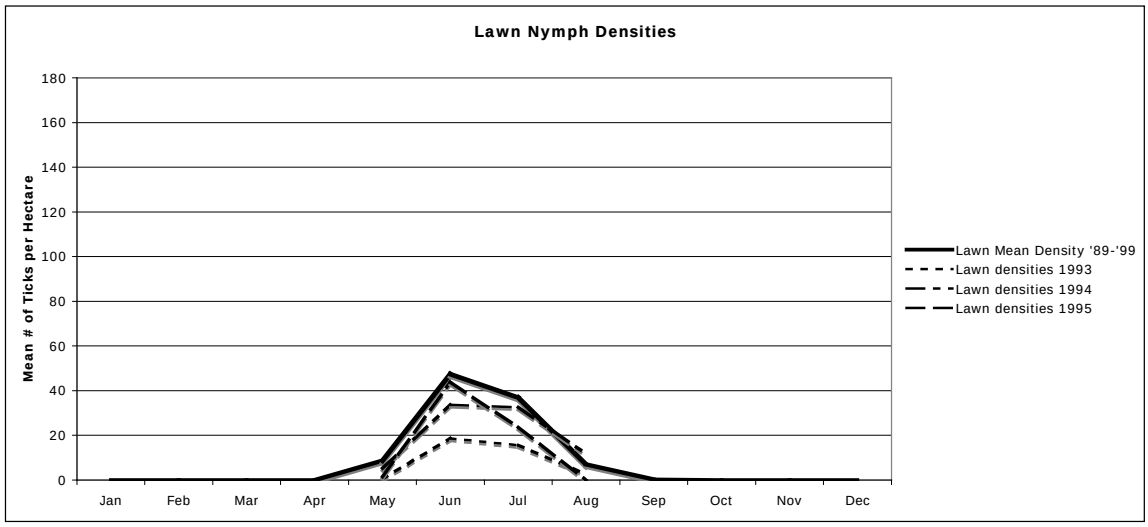


Figure A8. Palmer Z Index for 1993 and nymph densities for the three summers following.

1993





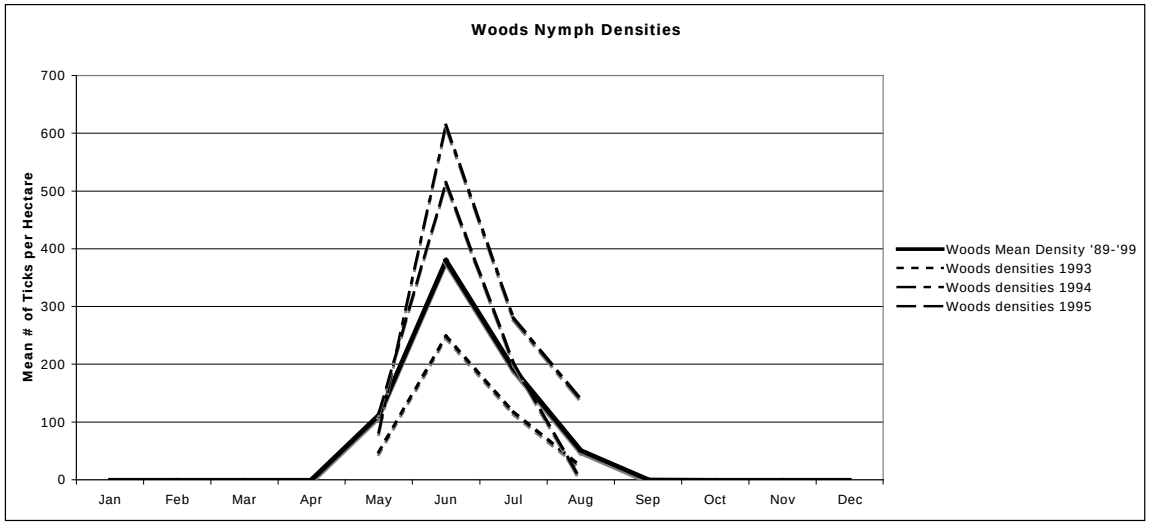
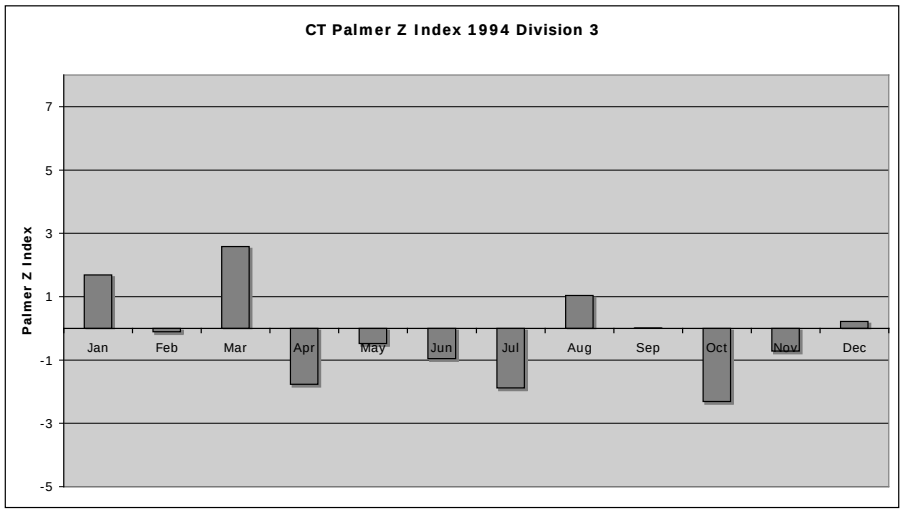
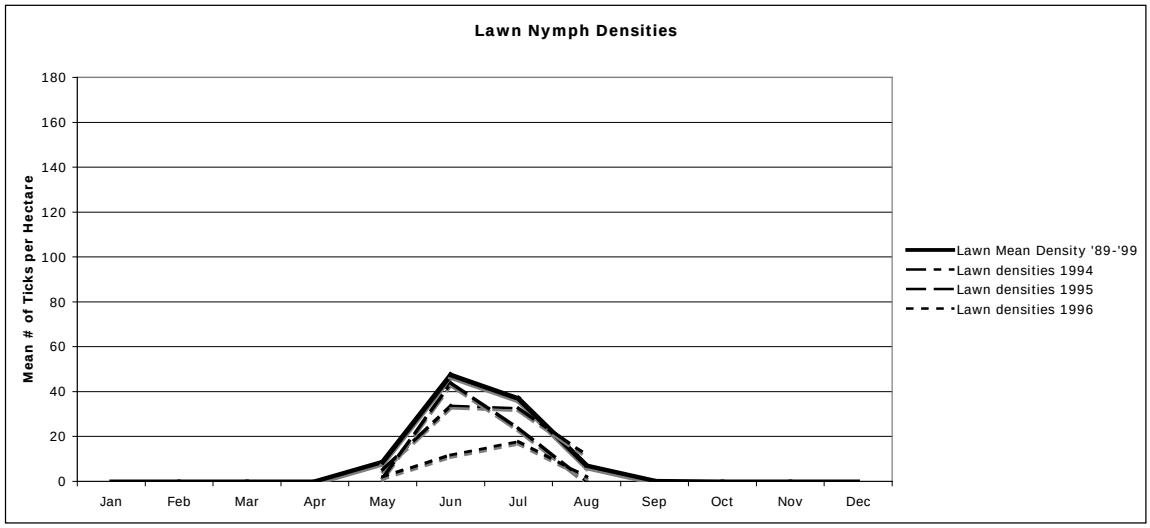


Figure A9. Palmer Z Index for 1994 and nymph densities for the three summers following.

1994





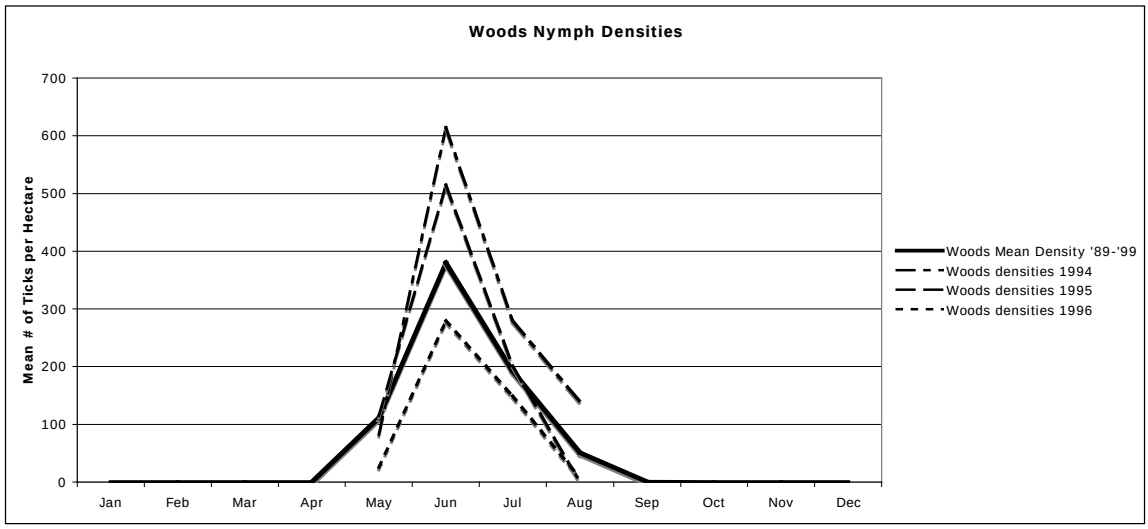
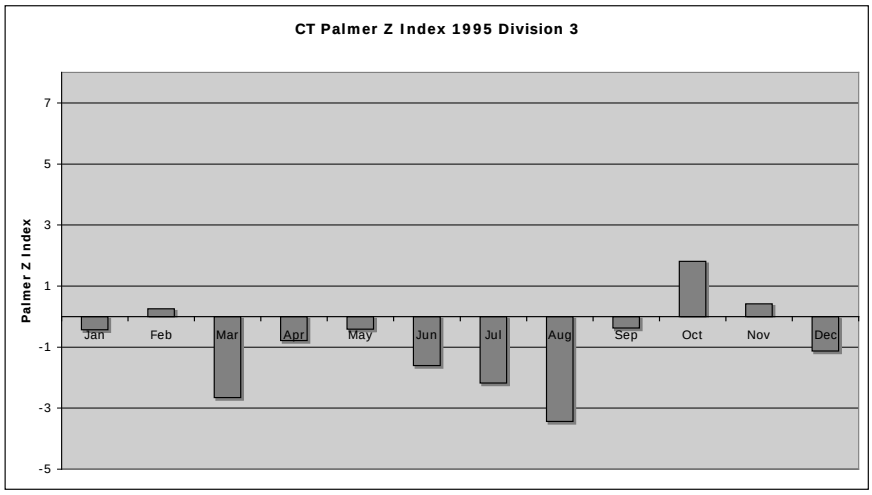
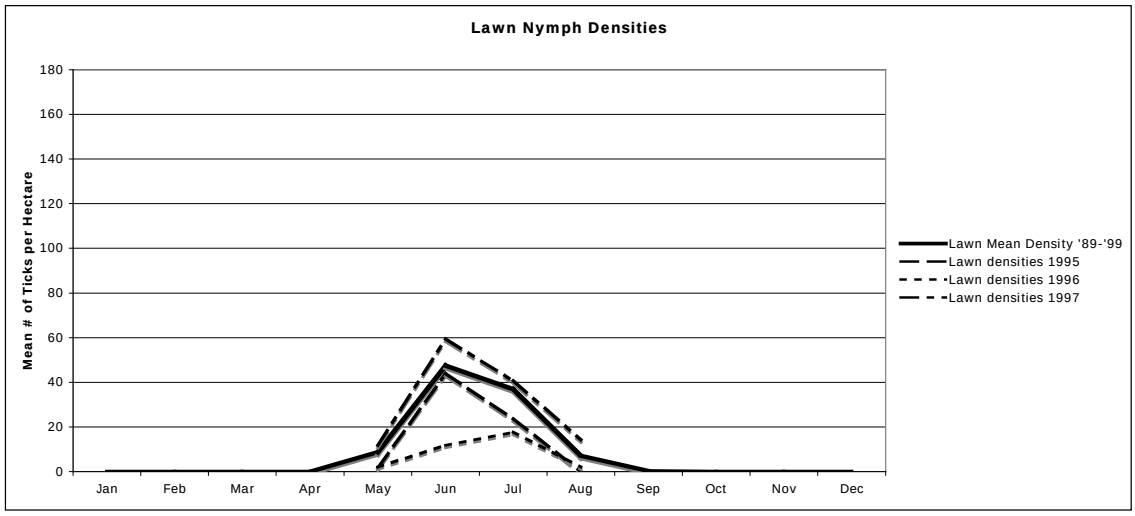


Figure A10. Palmer Z Index for 1995 and nymph densities for the three summers following.

1995





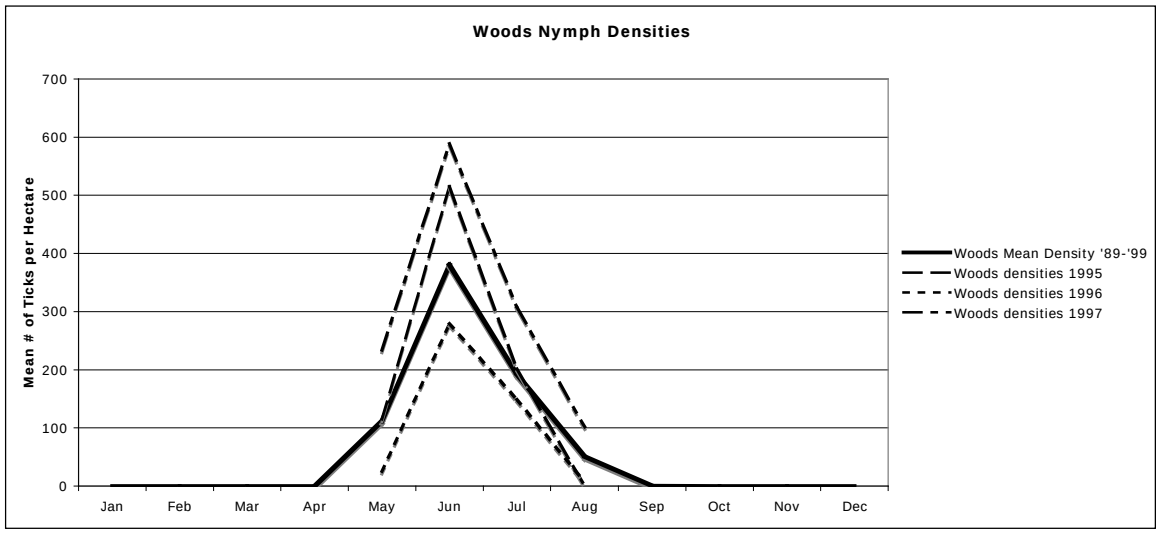
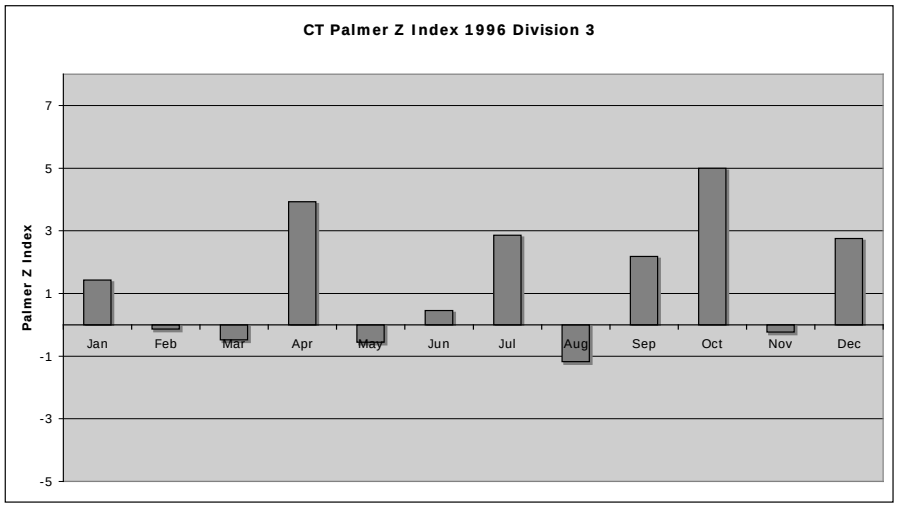
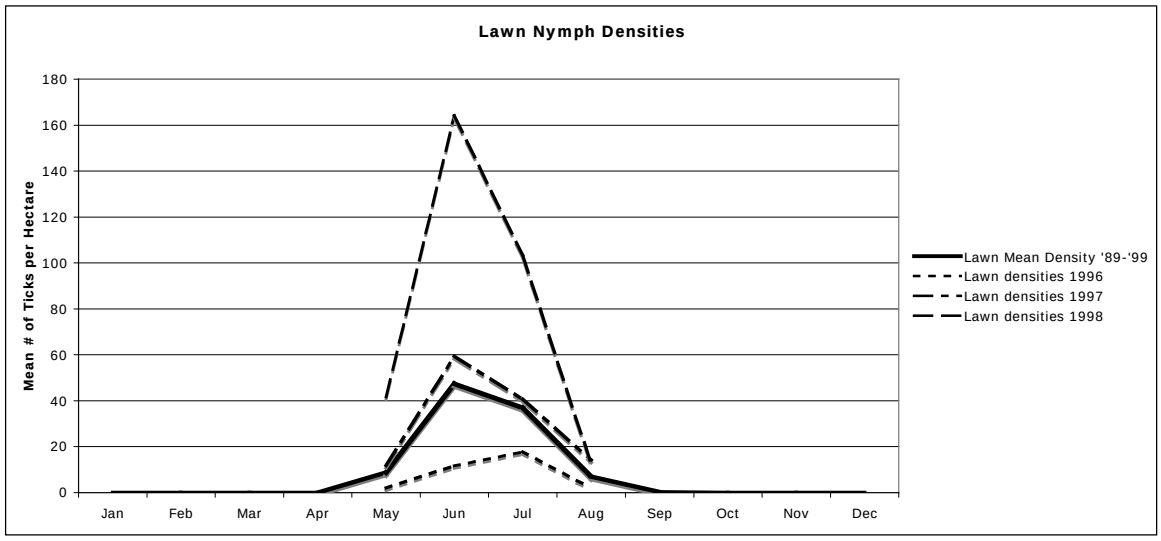


Figure A11. Palmer Z Index for 1996 and nymph densities for the three summers following.

1996





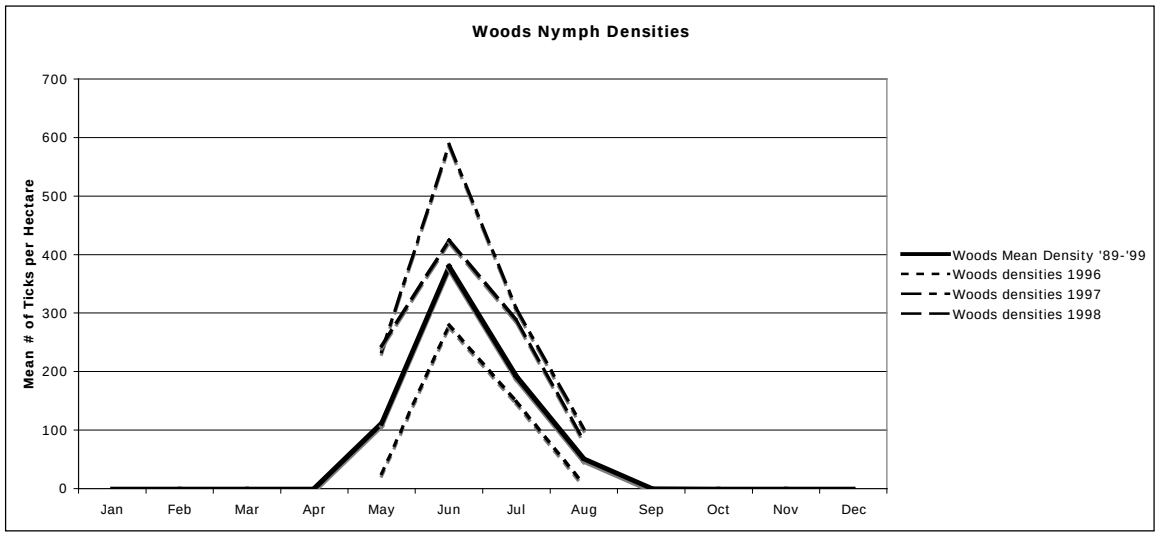
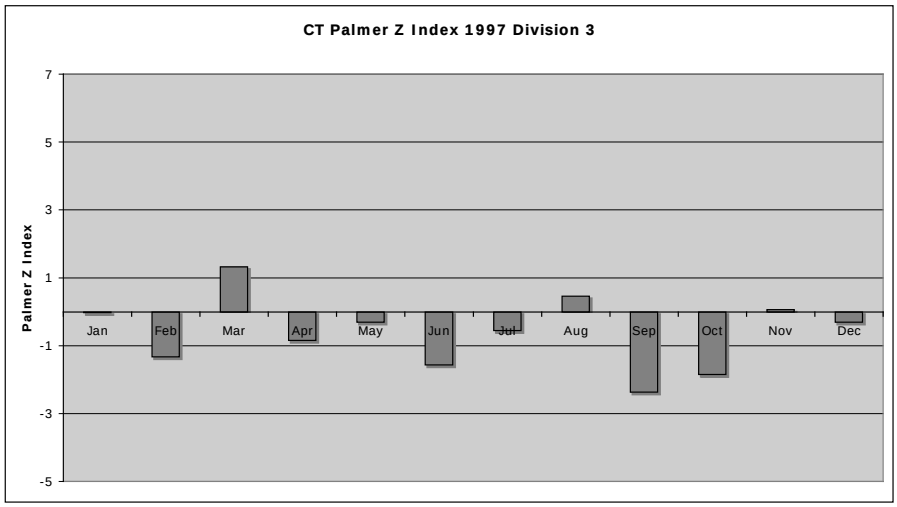
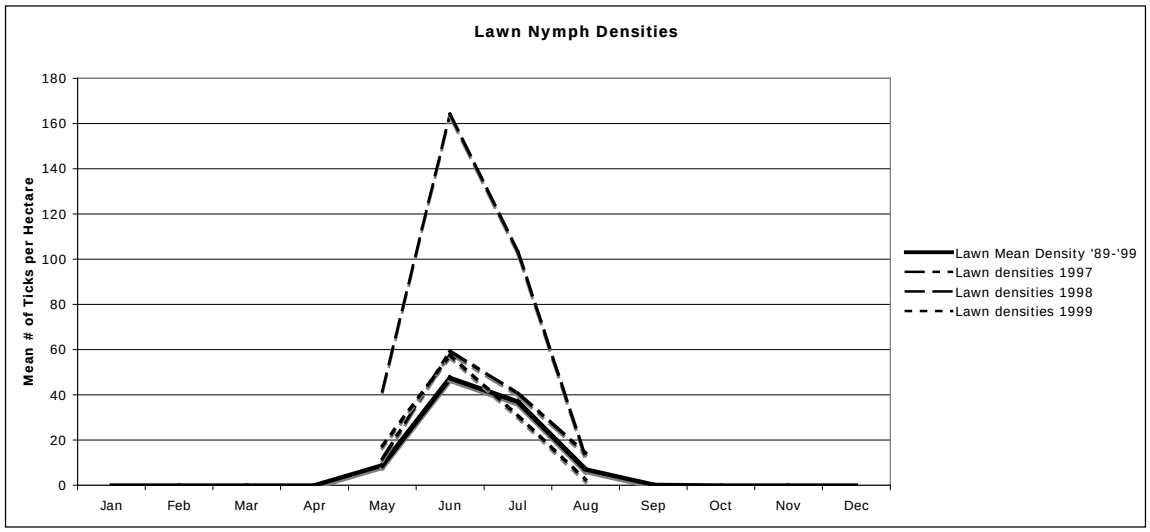


Figure A12. Palmer Z Index for 1997 and nymph densities for the three summers following.

1997





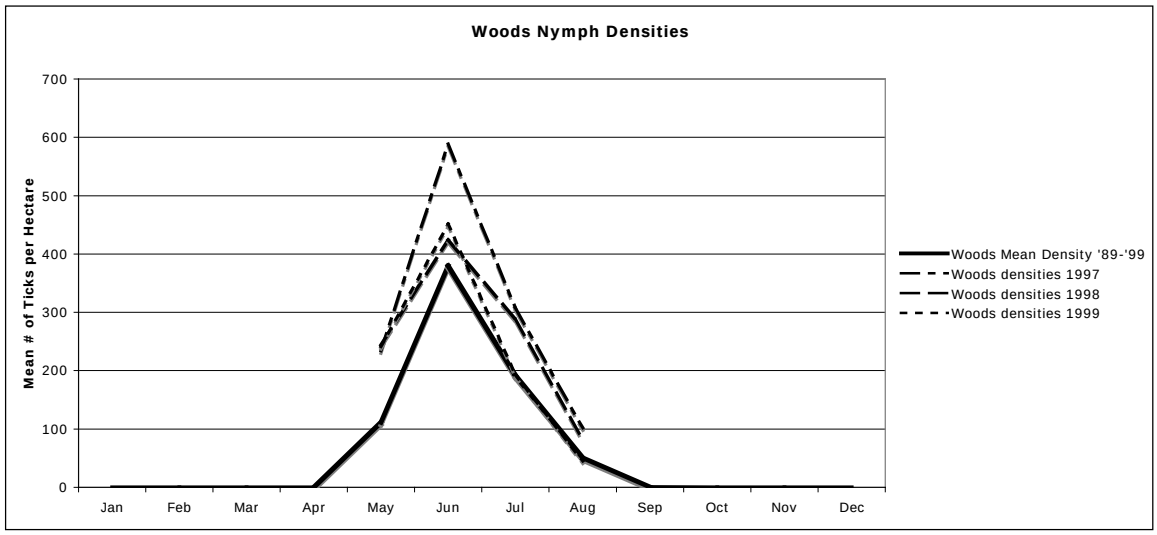
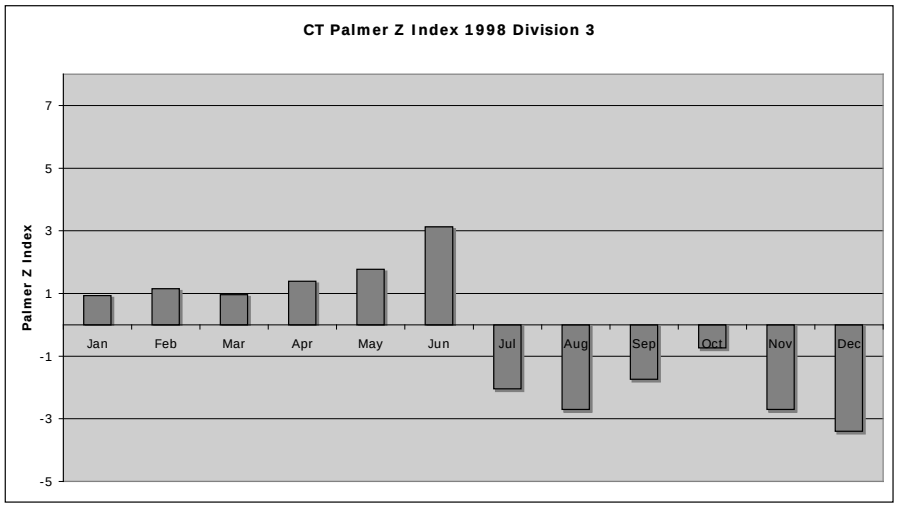
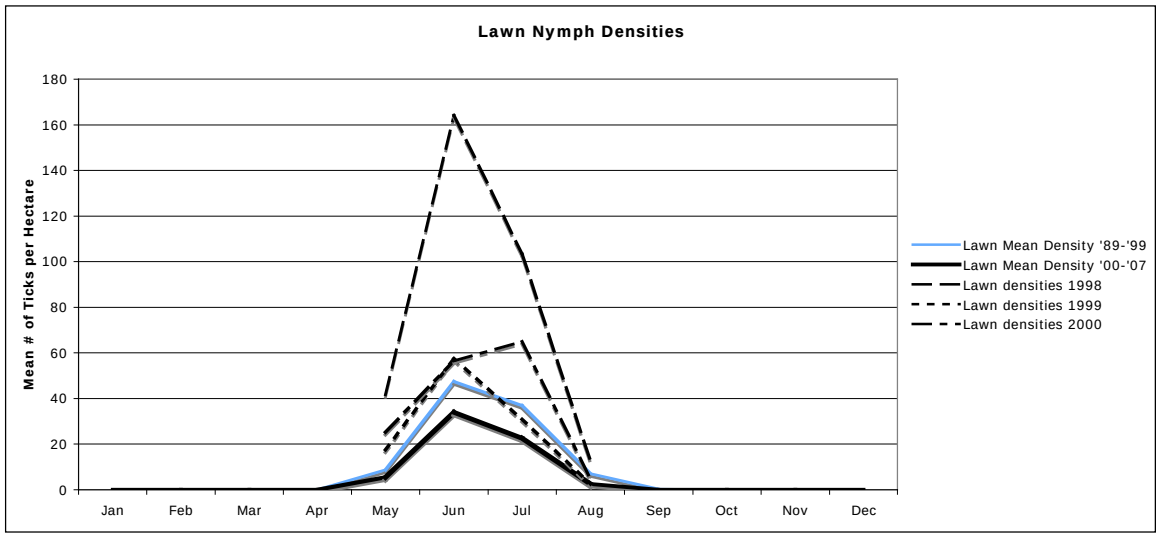


Figure A13. Palmer Z Index for 1998 and nymph densities for the three summers following.

1998





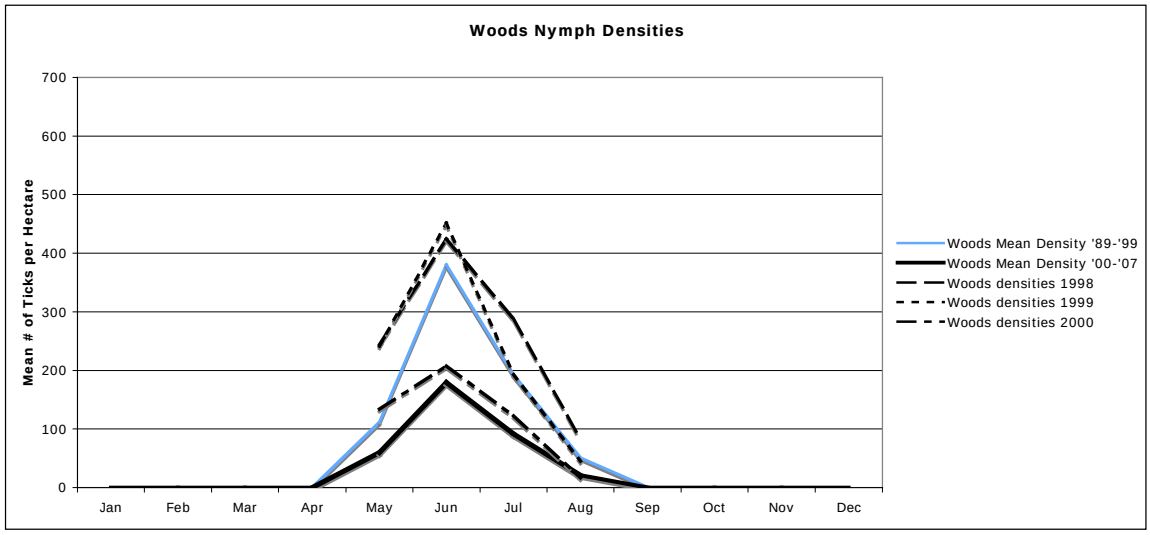
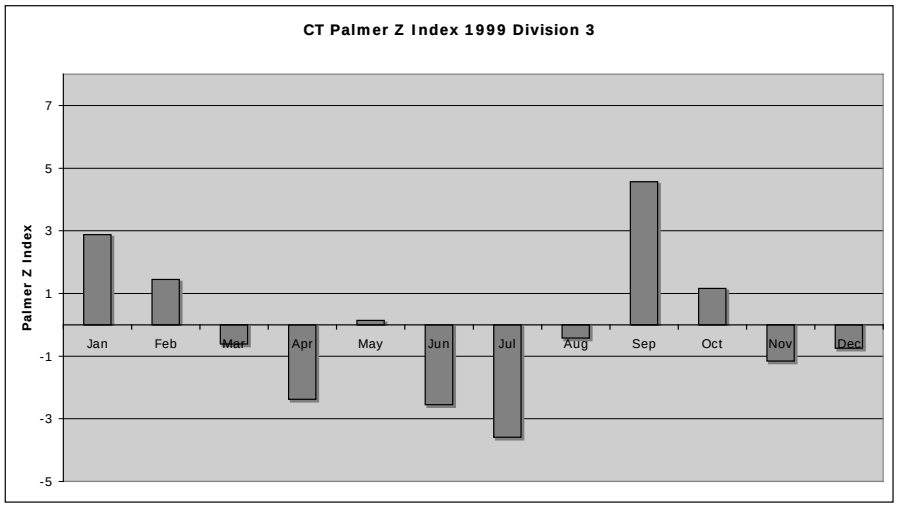
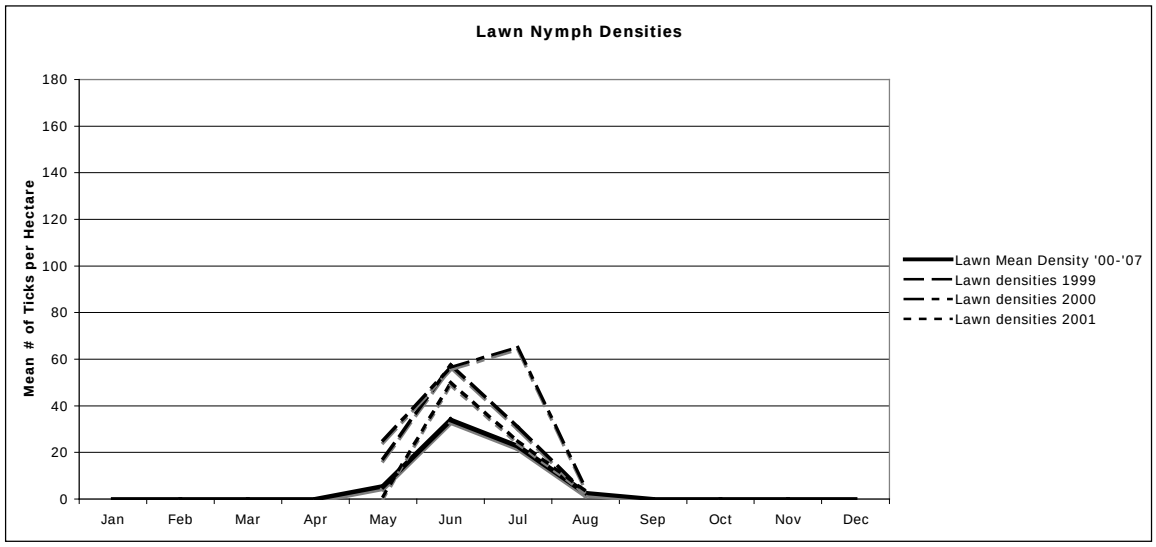


Figure A14. Palmer Z Index for 1999 and nymph densities for the three summers following.

1999





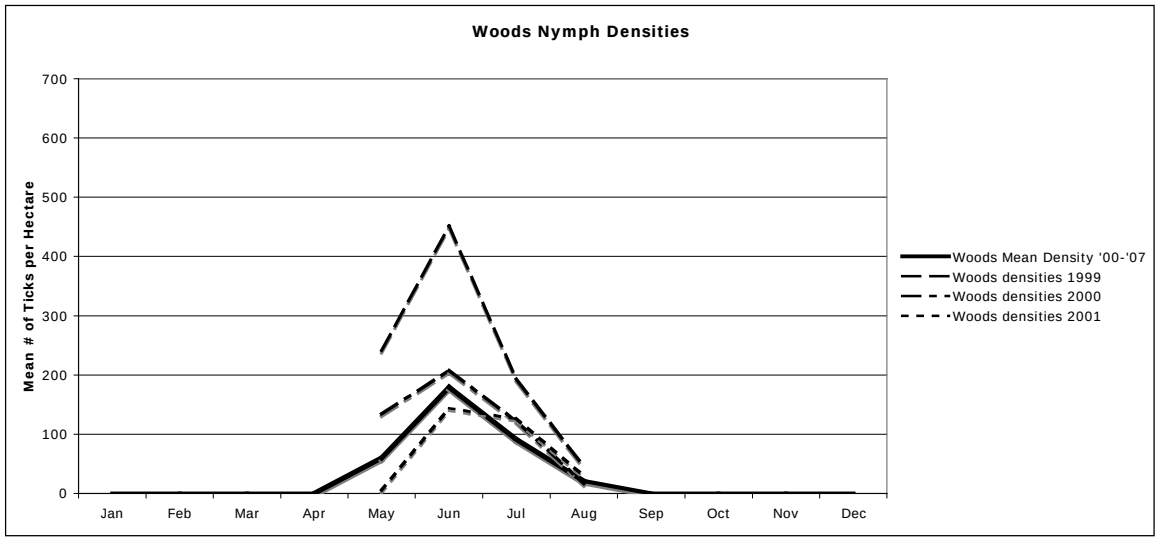
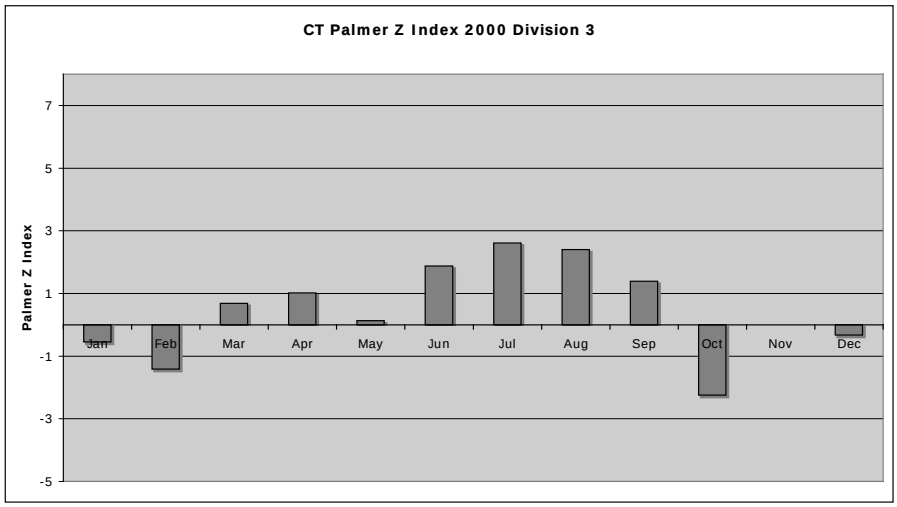
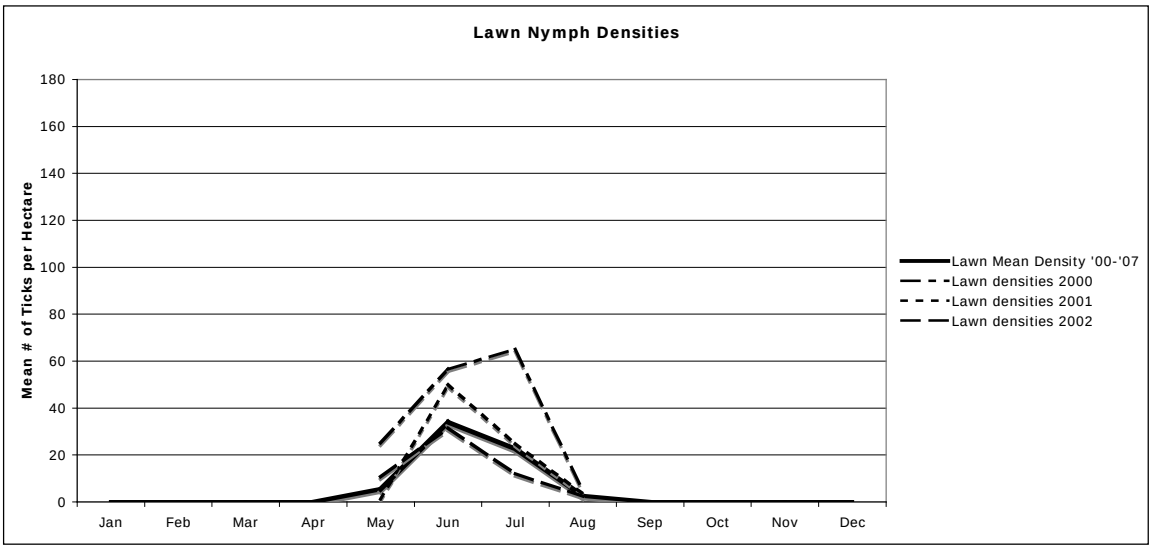


Figure A15. Palmer Z Index for 2000 and nymph densities for the three summers following.

2000





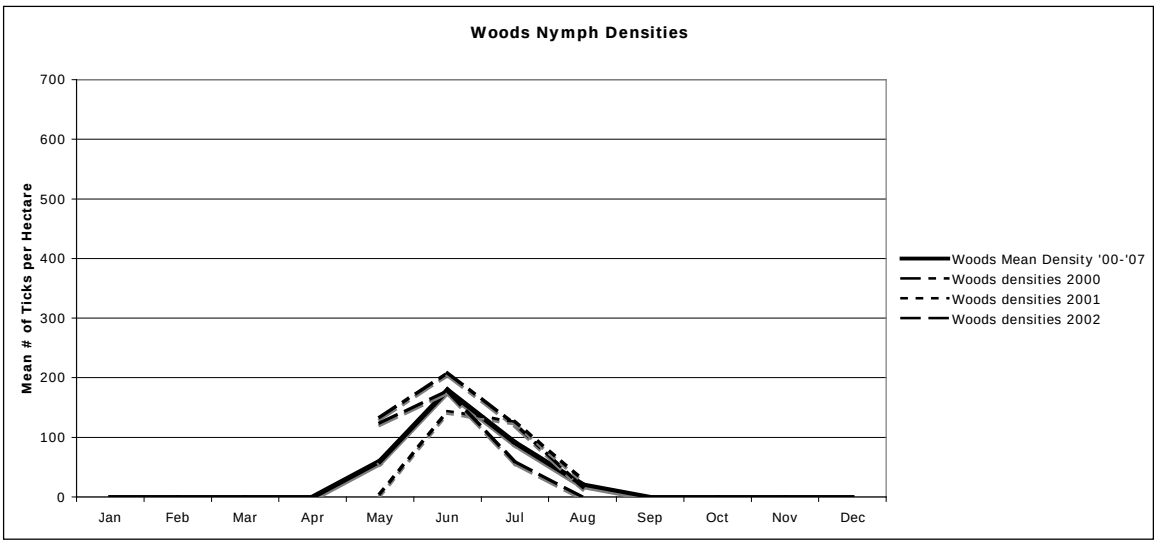
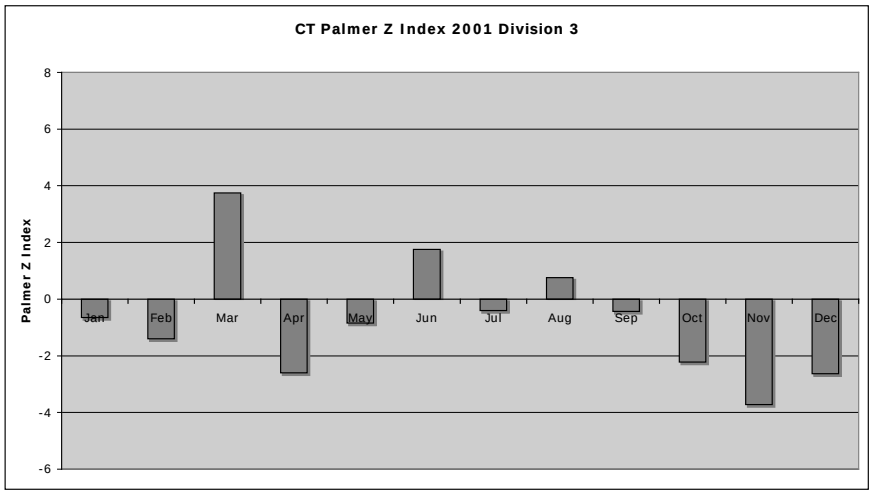
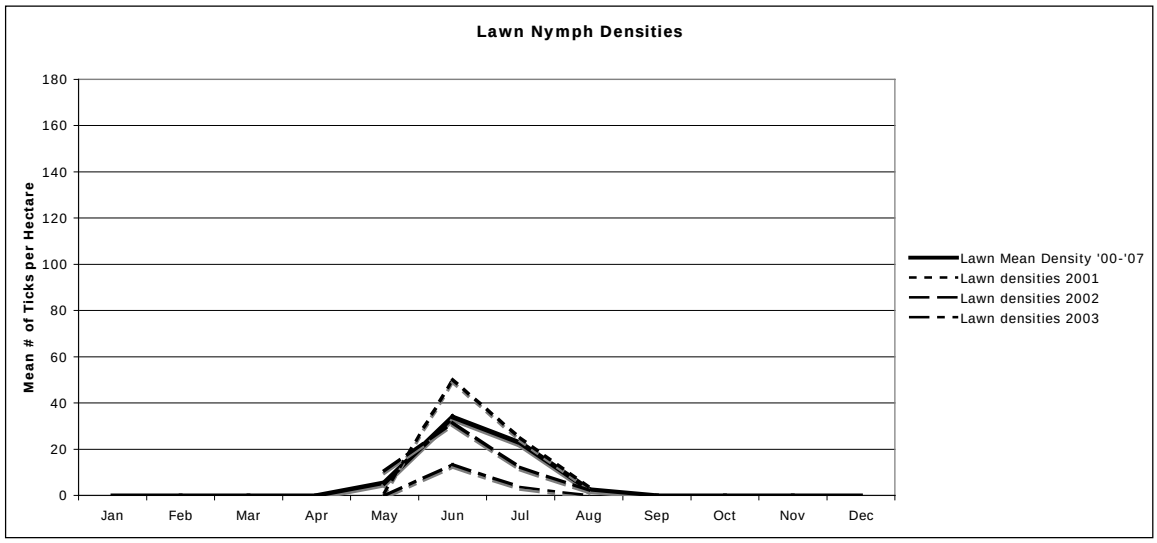


Figure A16. Palmer Z Index for 2001 and nymph densities for the three summers following.

2001





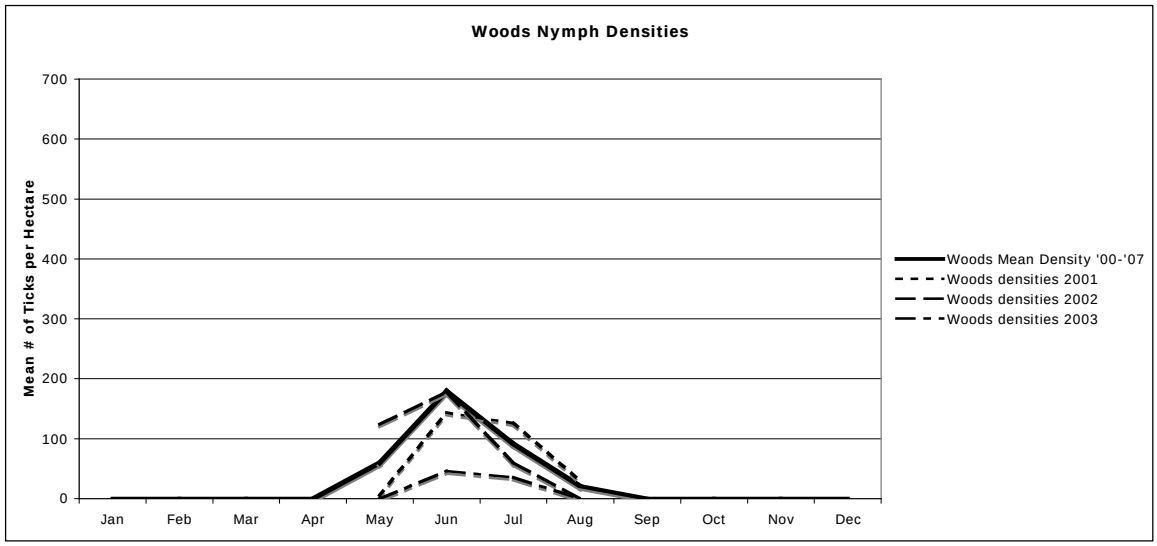
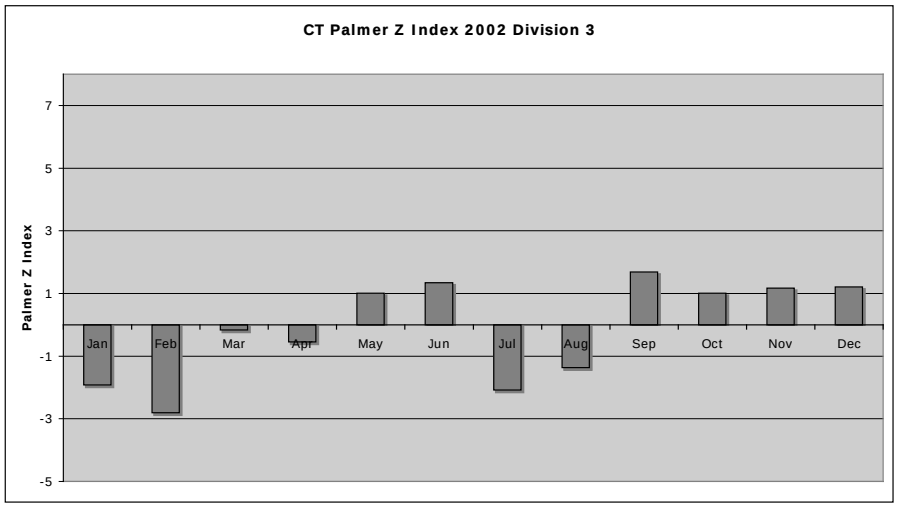
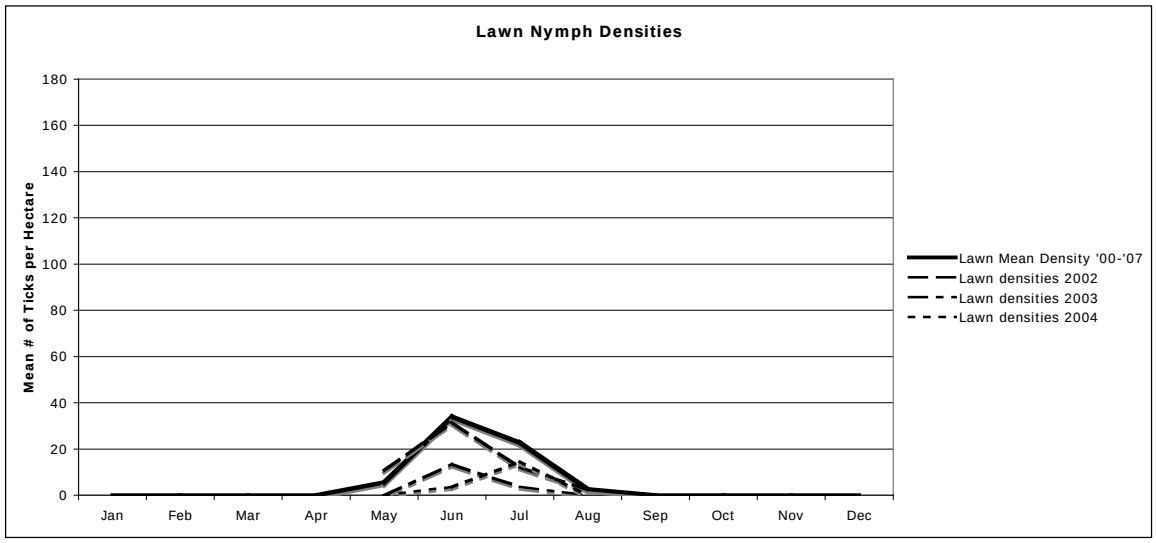


Figure A17. Palmer Z Index for 2002 and nymph densities for the three summers following.

2002





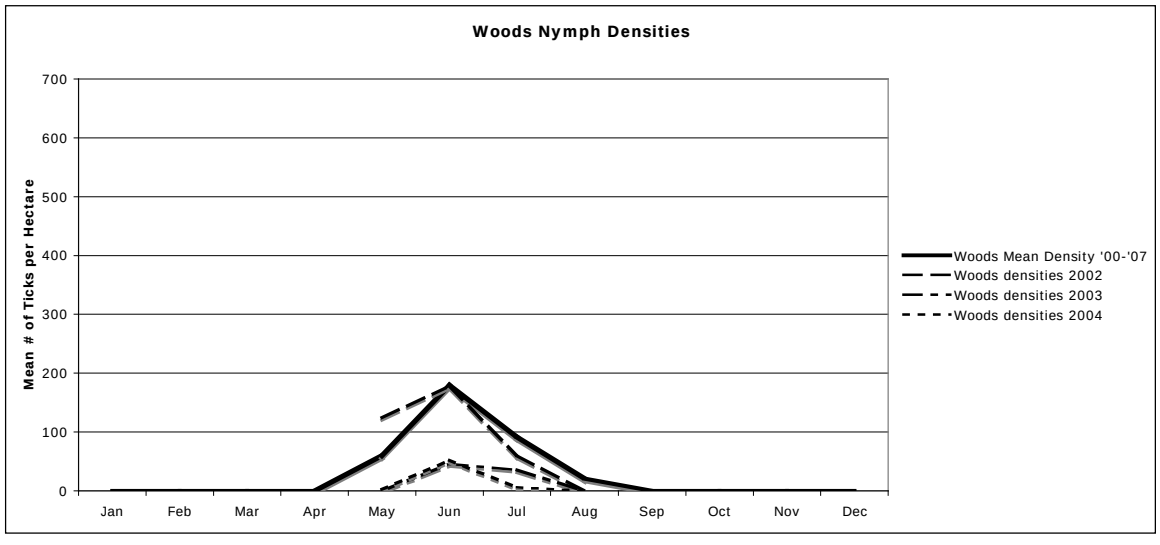
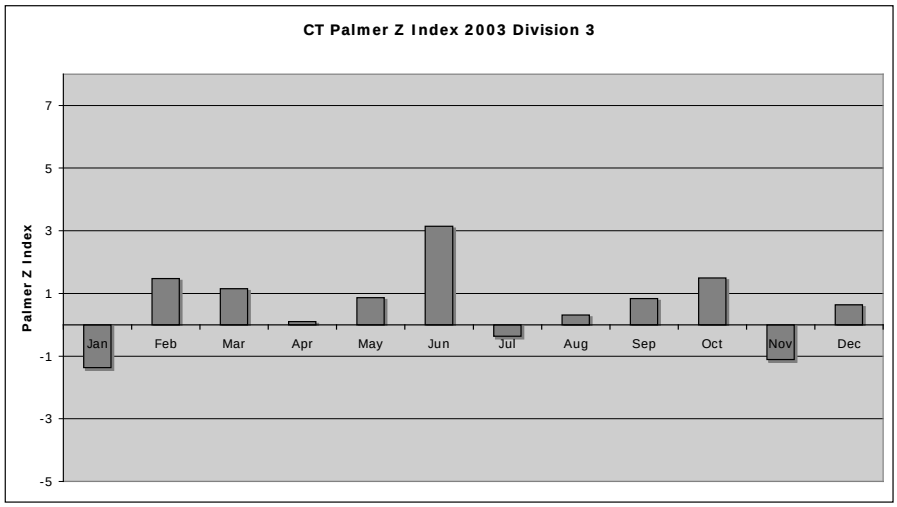
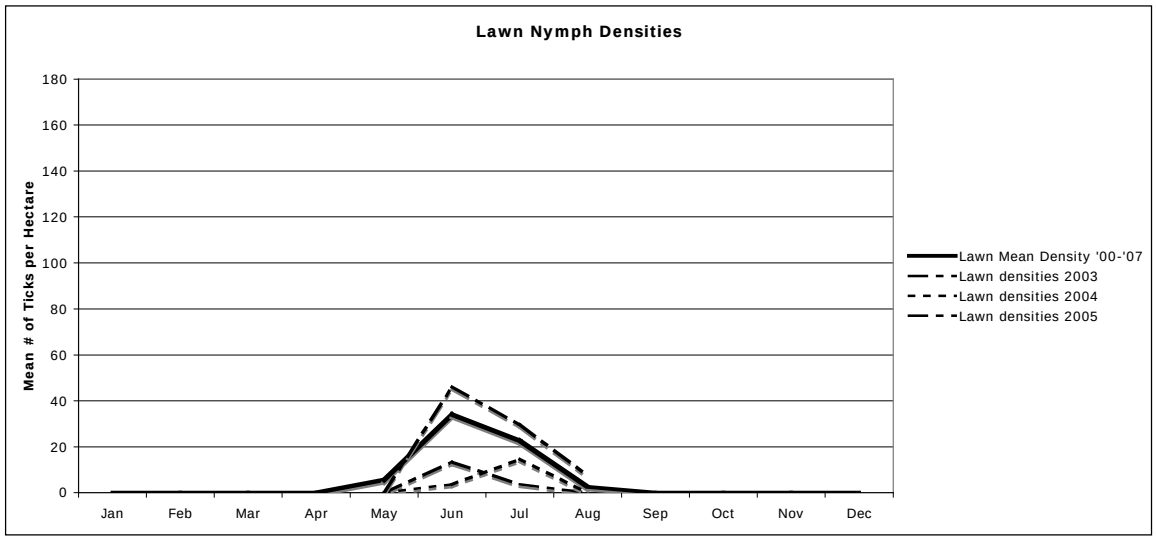


Figure A18. Palmer Z Index for 2003 and nymph densities for the three summers following.

2003





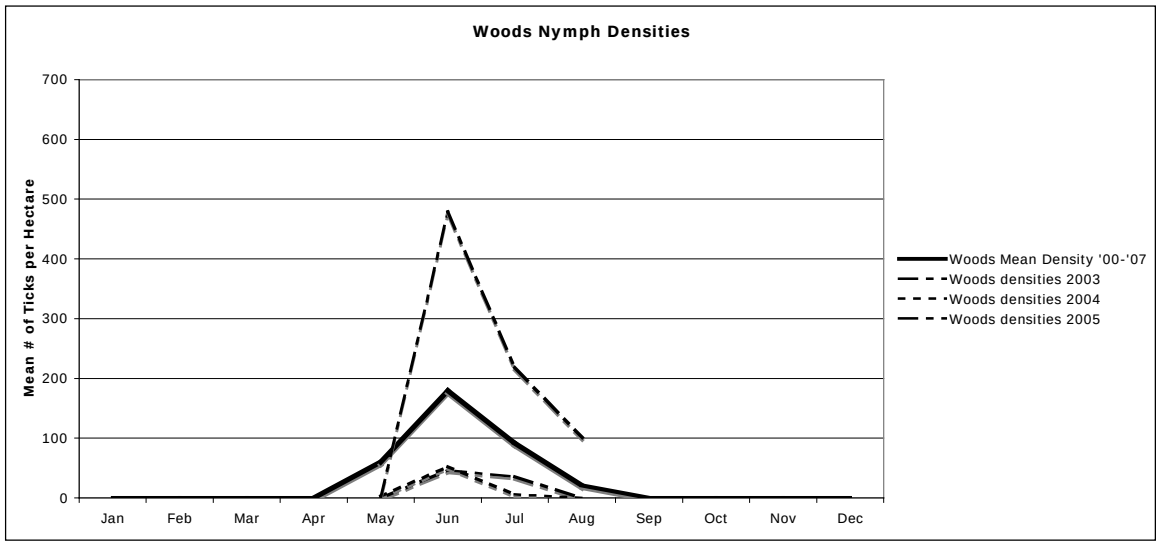
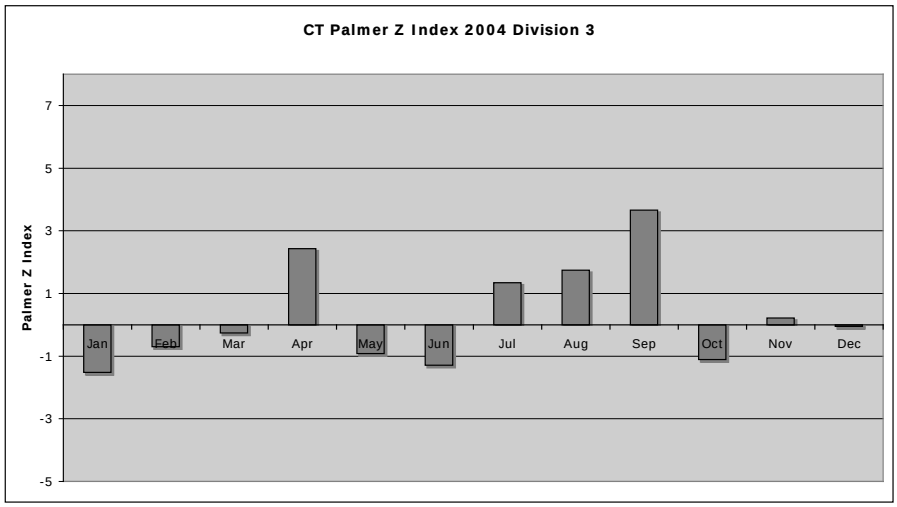
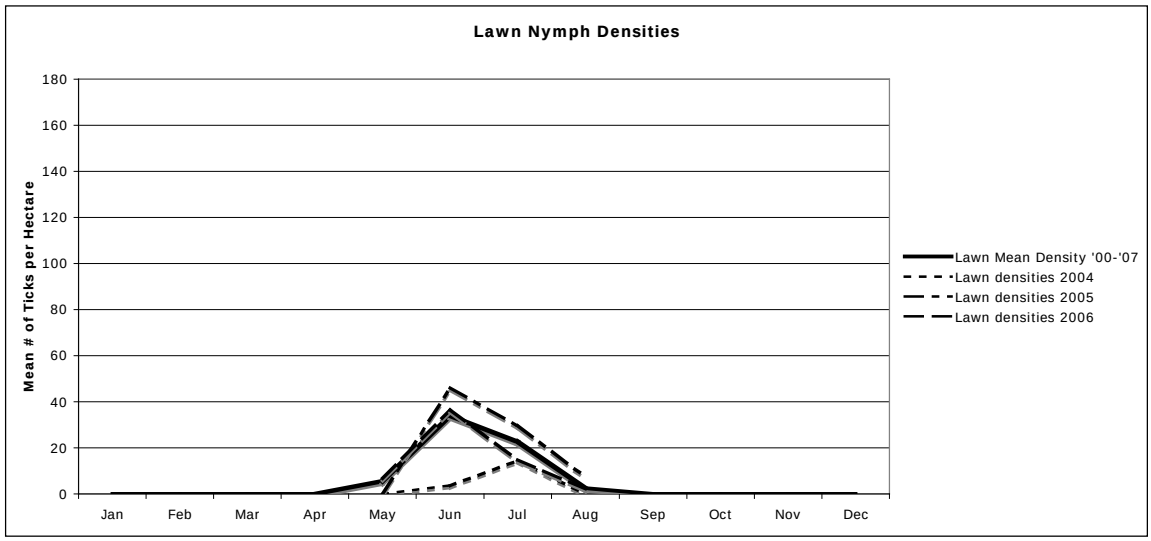


Figure A19. Palmer Z Index for 2004 and nymph densities for the three summers following.

2004





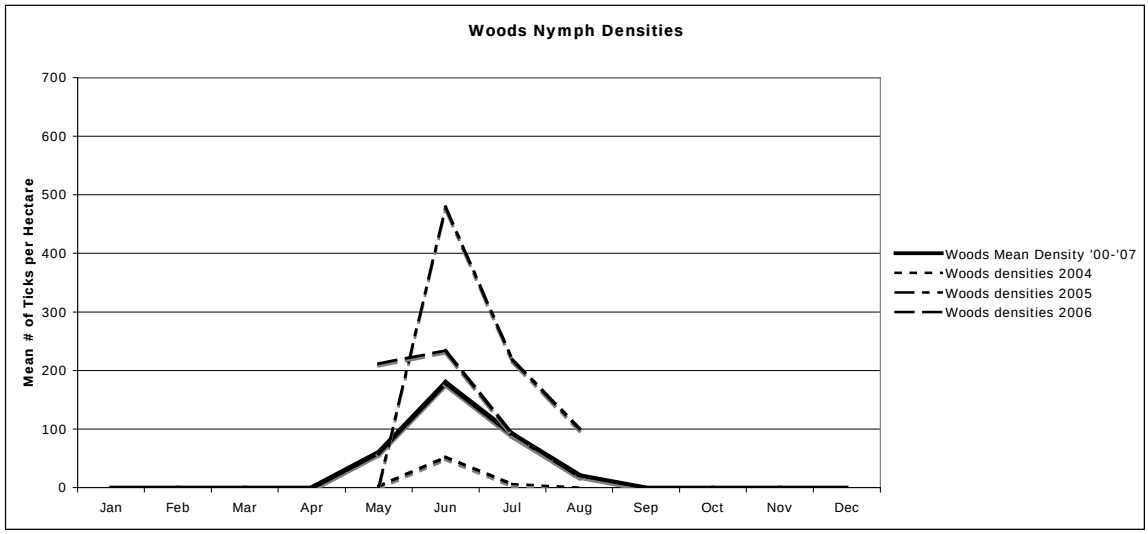
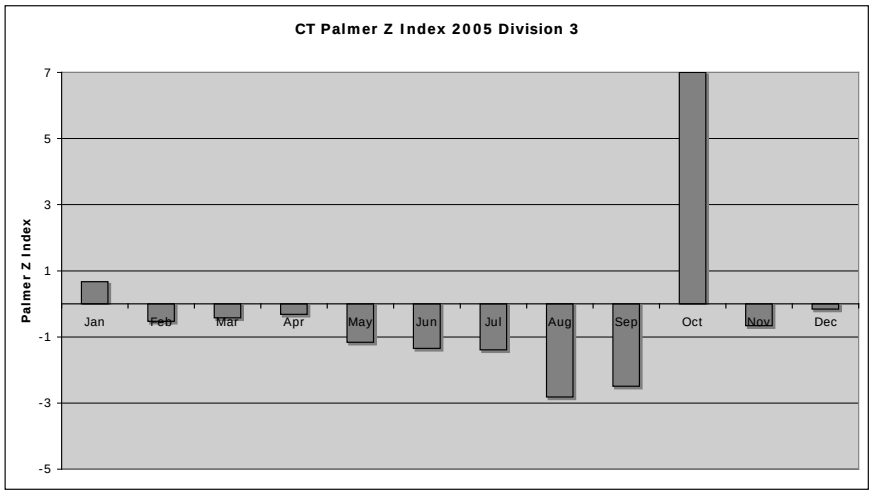
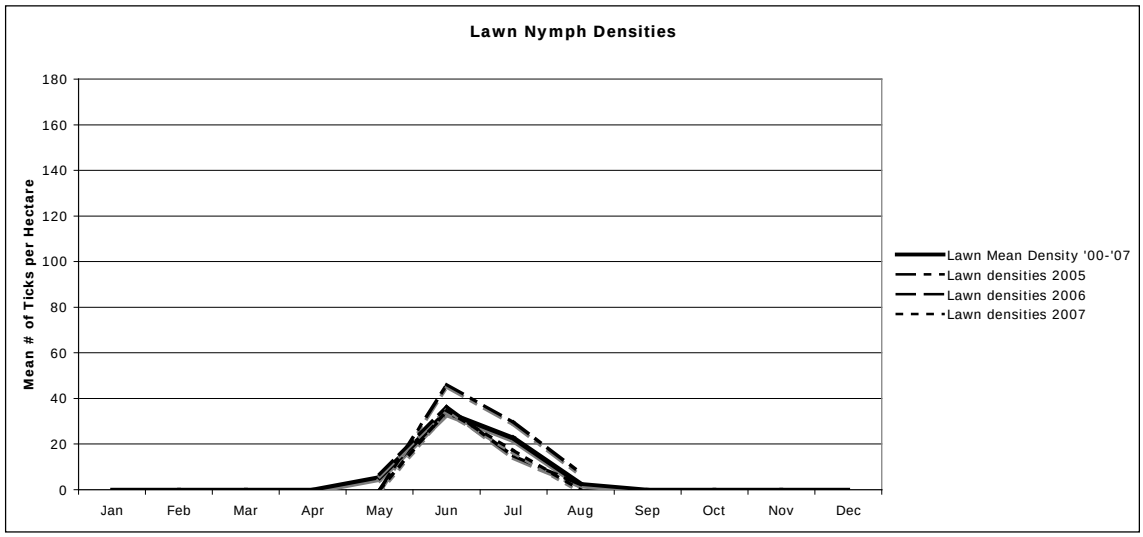


Figure A20. Palmer Z Index for 2005 and nymph densities for the three summers following.

2005





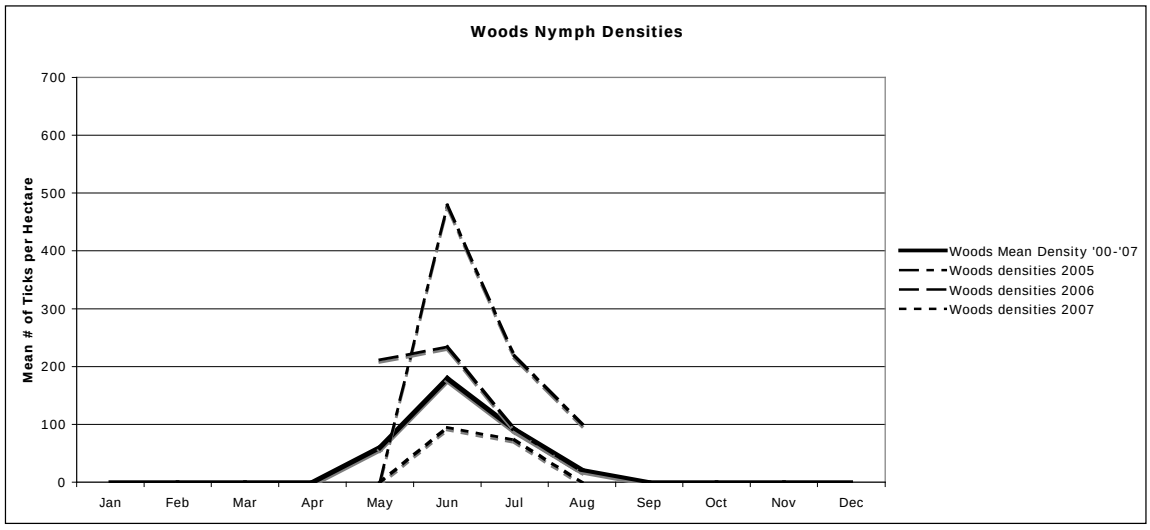
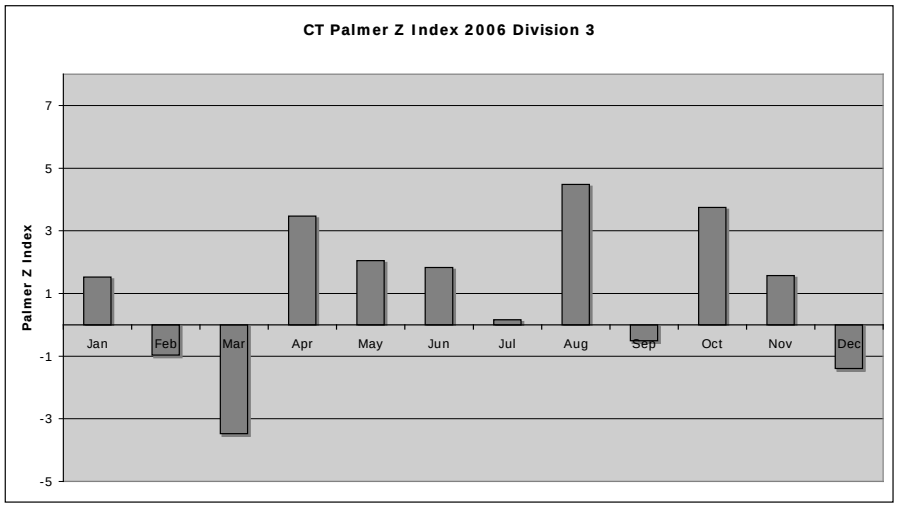
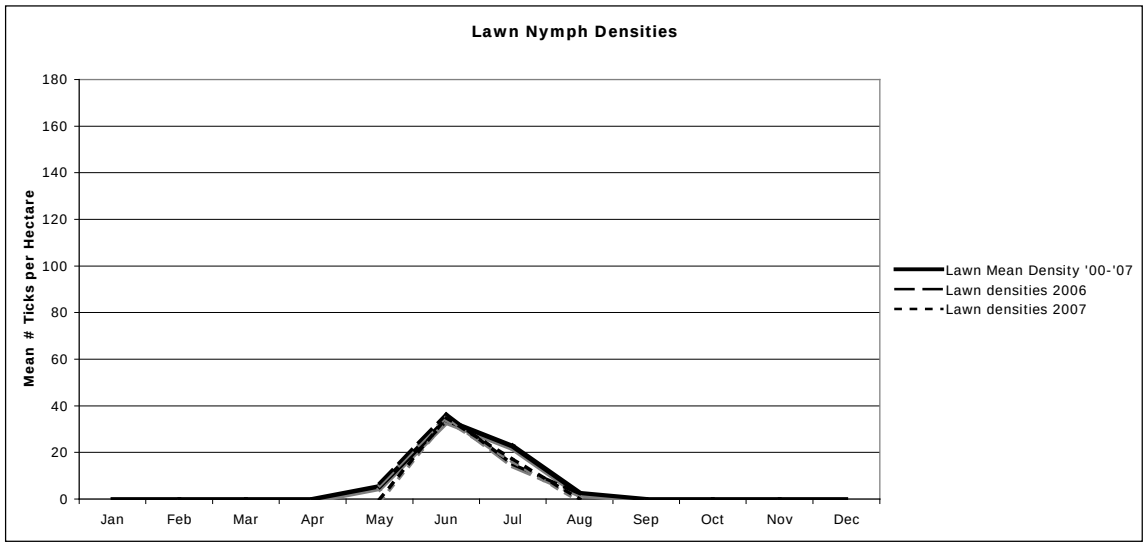


Figure A21. Palmer Z Index for 2006 and nymph densities for the three summers following.

2006





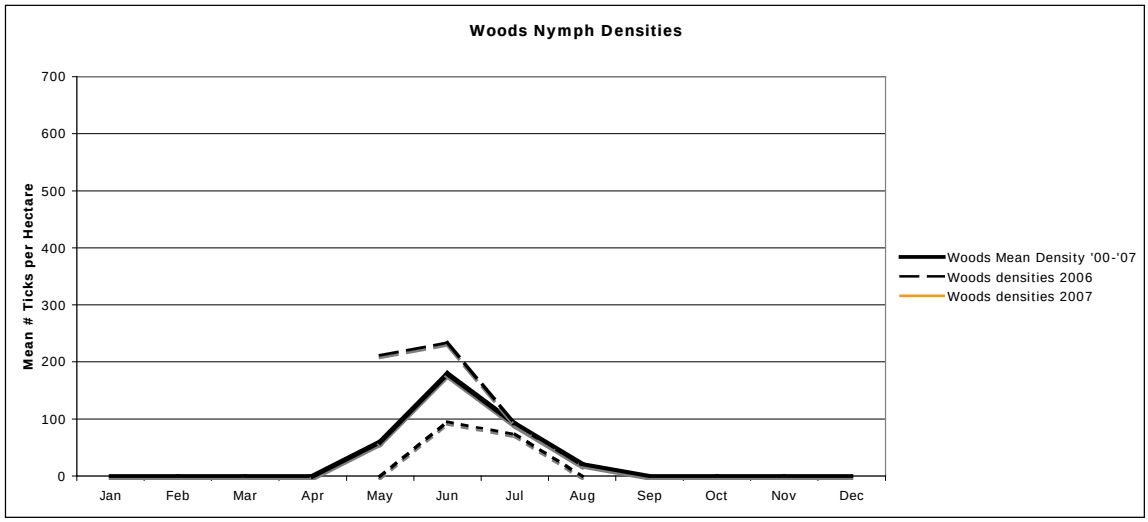
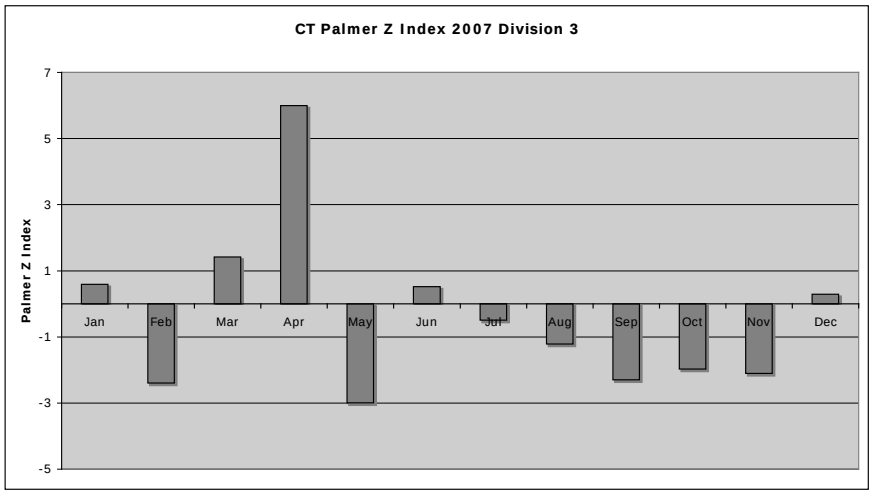
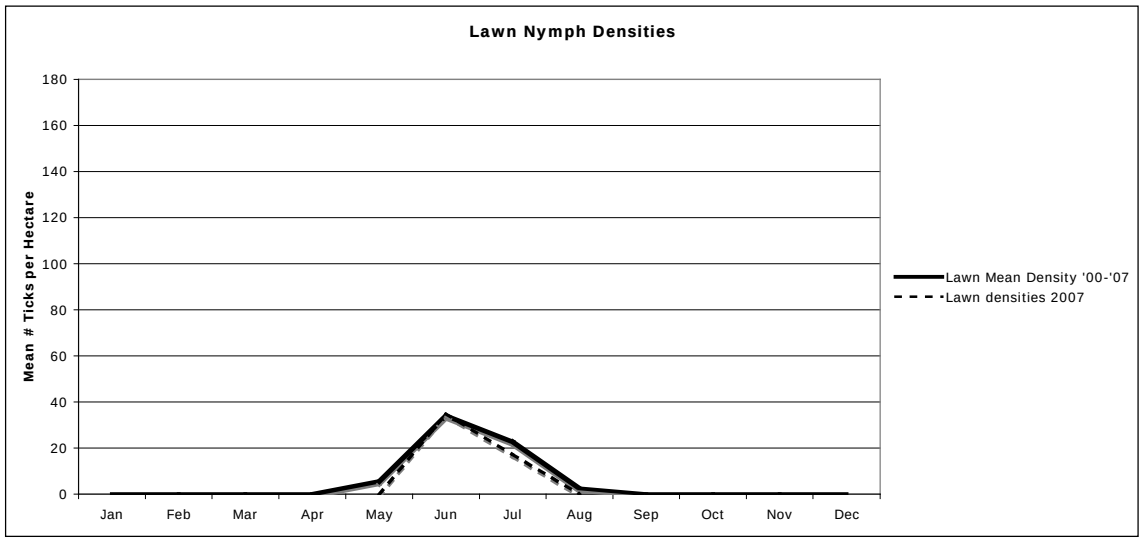
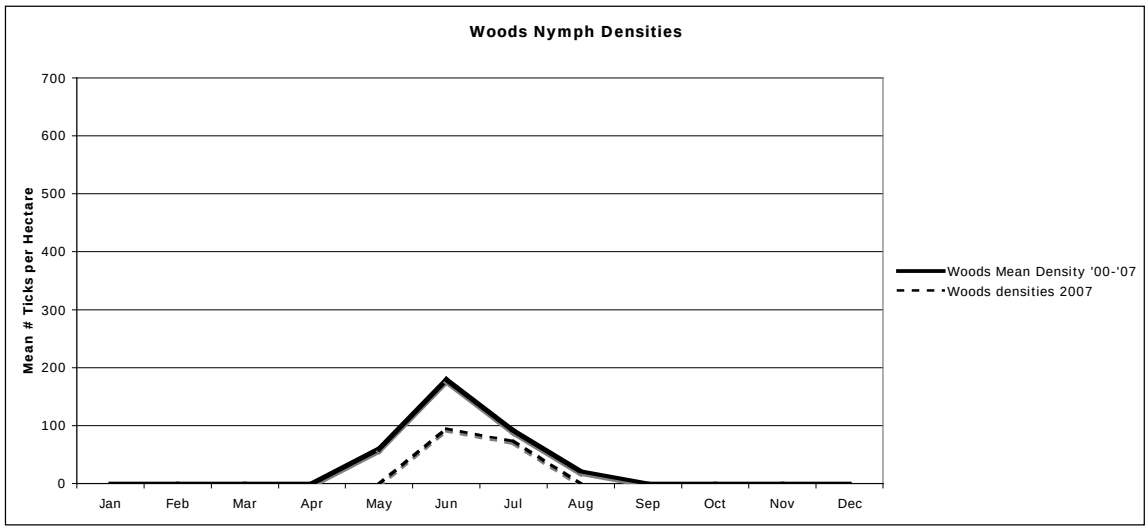


Figure A22. Palmer Z Index for 2007 and nymph densities for the three summers following.

2007







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